Centre for ecosystem management

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PERTH WESTERN AUSTRALIA

June 2010

Mine Voids Management Strategy (III): A Monitoring Strategy for Pit Lakes and Connected Waters

By, Dr. C. D. McCullough
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Department of Water (Western Australia)

Dr. C. McCullough BSc, MSc (Hons), PhD (Aquatic Ecotoxicologist),

Dr. Lu Y. L. Zhao BSc, MSc, PhD (Environmental Chemist),

Assoc. Prof. Mark Lund BSc (Hons), PhD (Aquatic Ecologist),

Ms. Michelle Newport (B.Env.Man.) Graduate Research Assistant.

Frontispiece

Plate 1. Dr. Lu Zhao sampling water quality in the WO5D pit lake.

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Australian Government

Water for the Future

Executive Summary

1. Pit lakes can form in open cut mining pits, which extend below the groundwater table. Once dewatering ceases, then groundwater, surface water and direct rainfall contribute to the formation of a pit lake.

2. Pit lakes are common in the Collie Basin in Western Australia (WA). They form a lake district consisting of 15 lakes, although two are currently being re-mined. As other mine operations in the Basin finish further pit lakes are anticipated, many of these potentially much larger than existing pit lakes (e.g., Muja). It is estimated that the total volume of water in Collie pit lakes exceeds 40 GL.

3. This report is Report Three of a series of five reports on water resources of the Collie Lake District that were all commissioned together by the Western Australian Government Department of Water.

4. Collie pit lakes have different physico-chemical characteristics than natural lakes, such as a small catchment vs. relatively great depth, less nutrients, low pH but high metal concentrations and poor acidity buffering.

5. The current demand for water in WA and its increasing scarcity means that Collie pit lakes represent a potentially valuable resource to both the environment and the community. As a result, a monitoring strategy for these pit lakes is required in order to achieve more stringent demands on pit lake conditions at relinquishment made by state and federal regulation and the desired end uses of local communities (McCullough *et al.*, 2009).

6. The purpose of this document is to recommend state-of-the-art monitoring design and sampling methodologies for environmental monitoring of pit lakes in the Collie Lake District, south-western Australia.

7. This report gives an overview of regional and international environmental issues related to pit lakes, current national guidelines and best practice international

operations and recommendations for monitoring pit lakes aquatic ecosystems. The purpose of monitoring selected indicators and their field sampling and analysis methods and techniques are described. The practical temporal and spatial issues targeting episodic events are also discussed in detail. Strategies for data analysis and reporting are suggested for maximising data value and to enable further monitoring strategy development during long-term monitoring. Based on these general principles of monitoring, quality assurance, health and safety and budget recommendations are included as well.

8. Many metals and metalloids in Collie pit lakes are below detection by ICP-AES methods, yet may be above environment and health background levels. Monitoring of heavy metals and metalloids should be made by ICP-MS to improve detection limits.

9. Although the water in the pit lakes appears to be suitable for a range of end-uses, a comprehensive ongoing water quality and biological monitoring is strongly recommended for these pit lakes in order to better understand whether certain poorly understood parameters are within relevant end use standards and guidelines.

10. Ultimately pit lakes will evolve to become dominated by biological rather than chemical processes; however the consequence of this is unknown. A detailed monitoring program to monitor changes in biological communities is also needed to provide information on whether the pit lakes will be able to provide ecological valuable environments to the region.

11. Little is known about remediation approaches that might be successfully employed to treat water quality issues in Collie pit lakes. Monitoring of pit lakes representative of different rehabilitation and remediation attempts should be made in order to advise which of these approaches may be of use with the predicted, much larger, new pit lakes.

12. Minimum recommended sampling is given in the below table. Major seasons e.g., temperate Summer/Winter or Dry/Wet seasons. *only required if end use required contact values e.g., swimming and water skiing. πOnly required if end-use requires environmental values e.g., as wildlife habitat.

Parameter	**Position**	**Historic lakes**	**New lakes**
Water			
Depth		Seasonally	Monthly
Temperature	Profile	Seasonally	Monthly
Conductivity	Profile	Seasonally	Monthly
pH	Profile	Seasonally	Monthly
Dissolved oxygen (as % saturation and mg/L)	Profile	Seasonally	Monthly
Turbidity	Profile	Seasonally	Monthly
Light attenuation (KDpar)	Profile	Seasonally	Monthly
Groundwater inflow/outflows		Seasonally	Seasonally
Surface water inflow/outflows		Seasonally	Seasonally
Chemical			
Dissolved metals/metalloids	Top and/or, bottom	Seasonally	Monthly
Major anions	Top and/or, bottom	Seasonally	Monthly
Major nutrients (TP, FRP, TN, NOx, NH_4, DOC)	Top and/or, bottom	Seasonally	Monthly
Buffering capacities (acidity and alkalinity)	Top and/or, bottom	Seasonally	Monthly
Biological			
Faecal indicator bacteria*		Monthly	Monthly
Aquatic macroinvertebrates[π]		Seasonally	Seasonally
Zooplankton[π]		Seasonally	Seasonally
Periphytic algae[π]		Seasonally	Seasonally
Phytoplankton (chlorophyll-a)		Seasonally	Seasonally
Crayfish[π]		Annually	Seasonally
Finfish[π]		Annually	Seasonally
Aquatic macrophytes[π]		Annually	Seasonally
Riparian vegetation[π]		Biannually	Annually

13. A better knowledge of groundwater near pit lakes; especially with regard to newly forming new pit lakes is essential. This could be achieved through both once-off investigations into catchment backfill characterisation and also from a simple groundwater monitoring program from bores placed close to representative pit lakes.

14. Replication of single depth e.g., surface water samples, are likely a waste of sampling effort and could be dispensed with to reduce sampling and analysis budgets without loss to any monitoring data value. Future monitoring attempts must, however, take into account basic limnological monitoring facets such as water column profiling. Specialised equipment will be required for this as lake water column depth is very great, particularly in the new pit lakes.

15. The quality and quantity of surface discharge from pit lakes also needs to be understood through monitoring and the ecological impacts of surface discharges needs to be fully investigated.

16. A comprehensive routine monitoring has now been developed (this Report) but still needs to be implemented in the pit lakes for a better understanding of whether or not pit lake water quality will meet end use criteria for current activities now (e.g., swimming) or proposed activities (e.g., fishing) into the future.

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1 Background

1.1 Pit lake formation

Open cut mining operations have become common practice over the last few decades in Australia, as a method of extracting commercially useful ore found near the surface. Since backfilling is normally unfeasible practically or economically, an open pit after completion of extraction operations is left. This is called a mine void. After mine operations are discontinued and dewatering ceases, most of those that extend below the natural groundwater table, fill by inflow of groundwater, direct rainfall, and runoff from adjacent drainage basins and the void catchment. Natural filling may take many years to complete. To reduce oxidation of mining waste and wall rocks, to inhibit the activity of acidophilic sulphur-oxidizing bacteria, and to promote anoxic conditions at the lake bottoms which may minimize the formation of acids and dissolved metals, some pit lakes are rapidly filled with stream or river diversions. The water qualities in such pit lakes depend on the filling water and geological catchments and are highly variable. Although the water level may continue to fluctuate as it equilibrates or as climate and local groundwater levels alter, once containing water, the empty mine void has now become a pit lake.

During the first half of the twentieth century, most pit lakes formed as a result of coal mining were located in North America. With the introduction of high-powered steam shovels in 1911, the surface mining industry became a major source of coal in the United States (Gibb & Evans, 1978) and left hundreds of pit lakes. Since the implementation of the federal Surface Mining Control and Reclamation Act of 1977, the formation of coal pit lakes in the United States has virtually stopped. However, coal pit lakes are still allowed and are sometimes desirable, considering that backfilling is normally unfeasible practically or economically. Also the needs of communities and ecology may allow pit lakes. There are some pit lakes being constructed at coal-mining sites in Canada (Sumer *et al.*, 1995) to serve as fish and wildlife habitat and for recreational use.

New mining technologies have led to a large increase in open cut mining of gold, silver, uranium, and base metals (Miller *et al.*, 1996). Open cut mining is currently in use mainly in Australia, Bulgaria, Canada, Chile, Colombia, Indonesia, Kyrgyzstan, Mongolia, Namibia, Peru, Portugal, Russia, South Africa, United Kingdom, United States, and Zambia. The number of future open cut mines is likely to continue with current and predicted demands for minerals and energy, the global financial crisis notwithstanding. Except for those in the most arid areas, deep open cut mines are likely to develop pit lakes when mining operations end. Given the large number of pit lakes that will form worldwide and the large volume of water they will contain, the quality of the water in these lakes will be of profound importance, especially in areas with scarce water resources.

1.2 Pit lake characteristics

Pit lakes differ physically from natural lakes in having a markedly higher ratio of depth to surface area (Figure 1). This is described by percent relative depth, which is defined as the percentage of a lake's maximum depth compared to its width calculated from its surface area by assuming the lake is approximately circular. A typical natural lake has a relative depth of less than 2%, although some may exceed 5%. Pit lakes commonly have relative depths between 10 and 40% (Doyle & Davies, 1999). This causes pit lakes easily stratify with the consequential changes in chemical characteristics with depth. Total dissolved solids and electrolytic conductivity tend to increase with depth; values near the bottom are often several times those at the surface. The hypolimnion (lower stratum) of a stratified lake has the tendency to contain low dissolved oxygen concentrations, if enough oxygen demand (chemical and/or biological) is high enough. The existence of a sub-oxic or anoxic (no oxygen) layer in a pit lake can have significant effects on the lake's chemical and biological characteristics and thus on its potential for remediation.

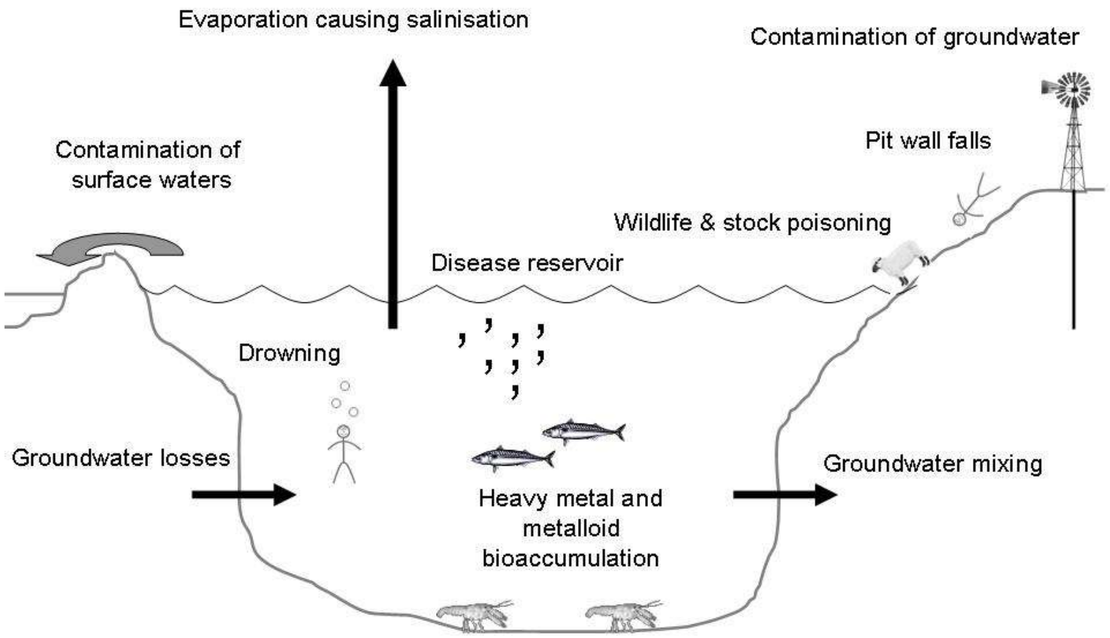

Figure 1. A conceptual model of the risks of pit lakes (after McCullough & Lund, 2006).

Where pit sides are battered for public access or to promote development of riparian (fringing vegetation) zones, deep pits will still have a bathymetry unlike natural lakes with steep sides below the battering. The size of mining pits in Australia ranges from relatively small urban borrow pits of about 100 m in diameter, to enormous open cut operations such as Mount Whaleback mine in the Central Pilbara, (WA) which will have final pit dimensions of 5.5 km by 2.2 km and a depth of 500 (Johnson & Wright, 2003). These new mining pit lakes have few natural counterparts in Australia, especially in depth. Furthermore, as the water level in the pit lake equilibrates, it is frequently deep within the walls of the open-cut, creating very little opportunity for natural slopes to the water surface; this also influences water mixing due to sheltering from winds (Huber *et al.*, 2008a).

As pit lakes typically have limited catchments, inflows of surface water tend to be small which may be useful in preventing worsening water quality from exposed geologies. However, where exposed geologies are not problematic, it may desirable for pit lake water quality to capture clean surface waters and small catchments may limit this. Pit lake water quality can be highly variable; particularly for acidity, salinity, hardness and metal concentrations which are primarily governed by the pit lake catchment hydrology and geochemistry (Miller *et al.*, 1996). For example, pit lake water quality may become acidic, through oxidation of reactive iron-bearing geologies as Acid Mine Drainage (AMD) (Klapper & Geller, 2002). Such acidic mine waters are often toxic to aquatic biota (Spry & Wiener, 1991; Doyle & Davies, 1999; Storer *et al.*, 2002; Stephens & Ingram, 2006). Pit lakes waters affected by salinity and acidity may also adversely influence nearby and regional groundwater resources and receiving environments, e.g., wetlands with contaminated plumes from flow-through pit lakes extending large distances down-gradient. The extent of such an impact may vary from insignificant in low hydraulic conductivity rocks and groundwater systems already saline, to considerable in high hydraulic conductivity rocks and naturally low-salinity groundwater environments (Commander *et al.*, 1994; Johnson & Wright, 2003). The majority of pit lake studies conducted in Australia have focussed on physical and chemical characteristics of water quality (Boland & Padovan, 2002; Jones *et al.*, 2008). These studies have demonstrated that pit lake water quality is influenced by many factors including climate, groundwater quality, depth, pit filling method and local mineralogy.

Pit lakes often have degraded water quality due to low pH and high concentrations of sulphate, and dissolved metals/metalloids. The chemical characteristics of a pit lake depend on the alkalinity of the local groundwater, the composition of the wall rocks, the chemistry of the surrounding vadose zone, and the quality and quantity of runoff from the surrounding land (Plumlee *et al.*, 1992; Davis *et al.*, 1993). Rock that is exposed to oxidizing conditions during dewatering can be a major source of acid, even though it lies below the water table before mining operations begin and after the lake fills (Miller *et al.*, 1996). The most common set of reactions producing acidity in mine lakes is the oxidation of sulphide and iron in pyrite (FeS_2) in the following two reactions (Castro *et al.*, 1999).

(1) $FeS_2 + 7/2\ O_{2(aq)} + H_2O \rightarrow Fe^{2+} + 2\ SO_4^{2-} + 2H^+$

(2) $Fe^{2+} + 1/4\ O_{2(aq)} + 5/2\ H_2O \rightarrow Fe(OH)_3 + 2H^+$

In natural systems pH is typically buffered by a carbonate buffer system (at pH of 6 to 8.5); however pit lakes of lower pH are often buffered by aluminium complexes (pH 4.5–5.5) or iron complexes (pH 2.0–4.0).

1.3 Australian pit lakes

Australia is among the top producers for many of the world's most important minerals (Mudd, 2007; Geoscience Australia, 2008). Major mining resources include diamonds, uranium, black coal, iron, gold, copper, lead, zinc, bauxite and mineral sands. Pit lakes occur in all states and territories in Australia However, most historic and contemporary mining activity is centred on the states of Western Australia (WA), Queensland and New South Wales (NSW) (Figure 2). Tasmania, Victoria, South Australia (SA) and Northern Territory (NT) are generally only important for certain minerals i.e., copper, gold, uranium, etc. (Mudd, 2007).

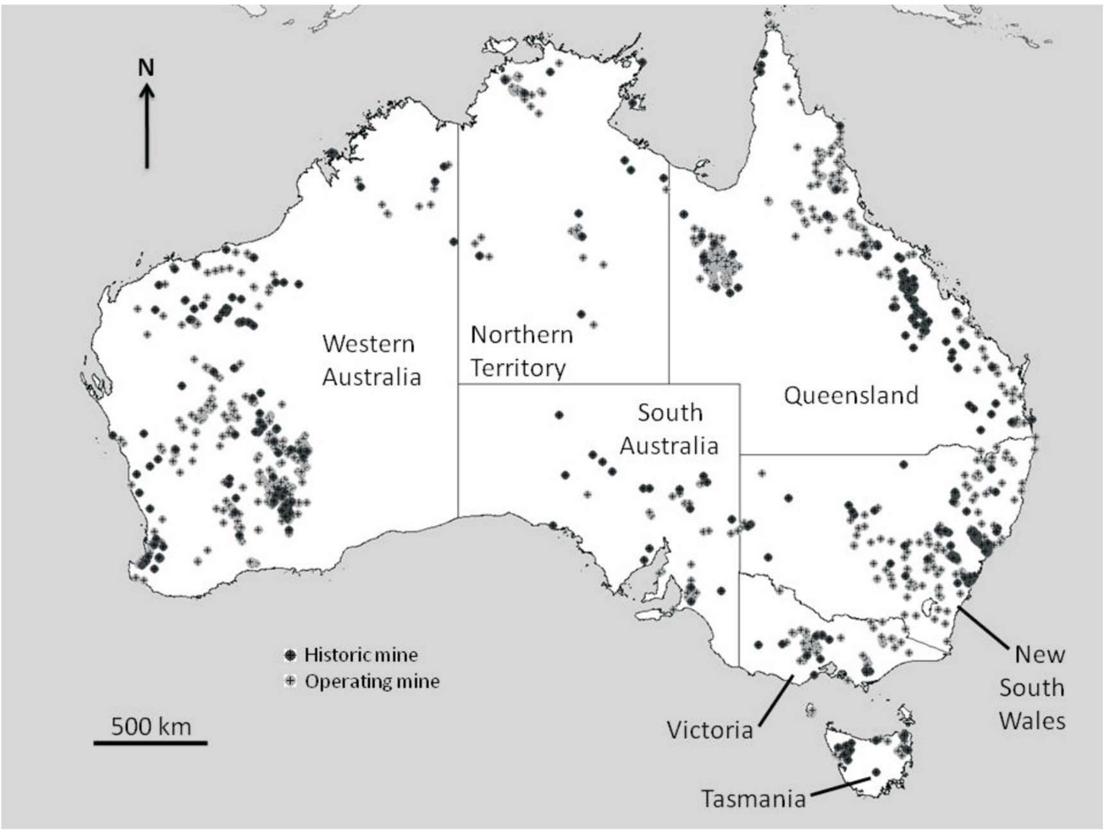

Figure 2. Distribution of historic and operating mines in Australia (after Kumar *et al.*, in press).

The mining areas also occur across a broad range of climatic regions (Figure 3). Approximately one-third of Australia is arid with rainfall less than 250 mm per year and another one third is semi-arid (250–500 mm per year). There are few areas where rainfall exceeds evaporation on an annual basis (Bell, 2001). Low rainfall and high evaporation rates exist in most parts of the country which may lead to net evaporation and the formation of hyper-saline pit lakes. Furthermore the groundwater in many parts of inland Australia is naturally brackish to hyper-saline. Low annual rainfall delays filling rates for new pit lakes facilitating oxidation of measures. A limited range of rivers and streams also limits opportunities for river rapid fill of pit lakes in many areas. However, surface discharge from pit lakes is also unlikely, which reduces a major source of environmental impact often seen in wetter climes. Contamination of regional groundwater in many arid areas can also often be a minimal risk as high evaporation rates ensure the pit lake remains a groundwater sink.

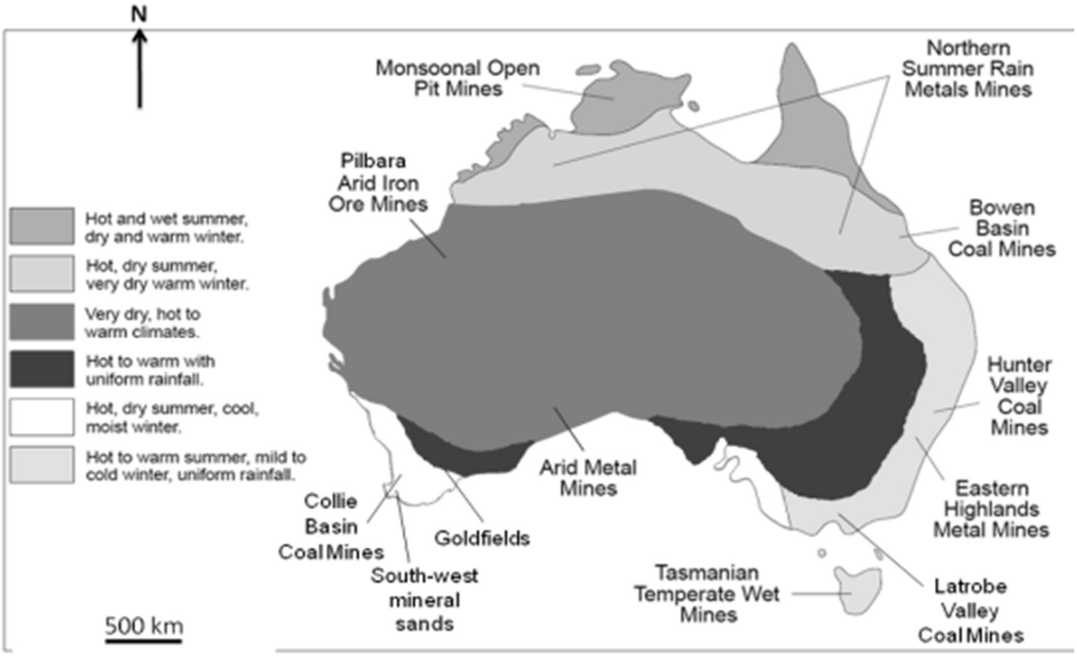

Figure 3. Australian pit lake classification after Mallet and Mark (1995), Johnson and Wright (2003) and (Kumar *et al.*, in press).

As one of the driest continents in the world and with the demand for water resources by industry and an increasing population, Australia may find pit lakes to be of significant potential use for both industry and surrounding communities (McCullough & Lund, 2006). It is not known how many pit lakes exist in Australia, since there is database for pit lakes at State or Commonwealth level. However, it was estimated in 2003 that there were 1,800 mine pits in Western Australia which potentially could form pit lakes (Johnson & Wright, 2003). Additionally, there are active or not-relinquished mining operations which add uncertainty to the number of pit lakes. Companies retain their leases over pit lakes with an option to over-mine as technology and economics alter the viability of their remaining resources.

A survey of mining operations in Australia found that 317 out of 517 mining operations contained potentially acid generating wastes (Harries, 1997). The same survey reported of the 176 mines that answered the questionnaire, 60 mines had water filled pits, but the pit lake water was similar to pre-mining groundwater. Nevertheless, seven sites had a total of 0.06 x 10^6 m^3 of acidic water at a pH of 2.5–3.5.

Australian pit lakes fall into four main categories in terms of their water quality. These are acidic (AMD affected), saline (can co-occur with AMD), neutral pH (but with some degree of contamination), and good water quality (but not necessarily comparable to natural regional water bodies) (Kumar *et al.*, 2012).

1. **Acidic** – As examples, water quality of pit lakes of Collie (WA), Collinsville and Mt Morgan (both Queensland) are all degraded by AMD. Nevertheless, Collie pit lakes have low pH and toxic concentrations of Al primarily due to low buffering rather than high acidity inputs (total S content of coal only 0.29-1% (Le Blanc Smith, 1993)). Collinsville and Mt Morgan show similar classic AMD conditions of extremely low pH and very high metal concentrations. These latter pit lakes also show effects of ongoing salinisation.
2. **Saline** – In drier regions where net evaporation exceeds precipitation, and surface inflow to the pit is largely restricted to direct precipitation, can result in dramatic increases in salinity leading to brackish through to hyper-saline lakes. Such hyper-saline pit lakes of degraded value may also contaminate valuable regional groundwater resources in the future. For instance, in semi-arid regions such as the Collinsville region, high rates of evapo-concentration result in significant increases in pit lake salinity each year (McCullough *et al.*, 2008b).
3. **Neutral** – Mary Kathleen and Thalanga (Queensland), Ranger (Northern Territory) and Wedge Pit (WA) pit lakes have generally good water quality that is nevertheless contaminated by one or more metals; in these cases Cu, Zn, U and As respectively. Nevertheless, these pit lakes remain well suited to a variety of end-uses as individual contaminants can often be more readily remediated or treated than more complex pit lake chemistries. For example, As contaminated water is extracted from bores a few meters away from Wedge Pit, treated and used to supply potable water to Laverton.
4. **Good water quality** – Kemerton (WA) is a silica sand mining operation with few geological considerations or mining processes that result in contamination of pit lake waters, hence water quality is very good. However, there remain significant differences in lake shape and water quality compared to shallow naturally acidic wetlands nearby (McCullough & Lund, 2008).

1.4 Pit lake water quality over time

Water quality in pit lakes plays a dominant role in determining the range of end uses the lake can be used for (McCullough & Lund, 2006). The chosen end use will necessitate a certain water quality within the pit lake and remediation technologies will be needed in many cases to achieve the required end use water quality. Research is therefore required into water quality development in pit lakes by incorporating hydro-geological, limnological, biological and biogeochemical processes.

Current predictive models do not adequately account for sufficient of these processes for pit lakes to allow for useful predictions to be made (Jones, 1997). Instead, such models are likely to provide information for advancing current conceptual models and provide advice of pit lake response to different management scenarios (McCullough *et al.*, 2009). There are no Commonwealth or state guidelines for developing pit lakes as useful water resources. For instance, acidic and/or saline pit lakes influenced by AMD with acidic and metal contaminated water will need to be remediated using either chemical or biological methods (McCullough, 2007; McCullough *et al.*, 2008a; Neil *et al.*, 2009). Pit lakes contaminated with one or two metals but otherwise with good water quality can be used for a range of activities following chemical treatment such as selective precipitation. On the other hand, pit lakes with good water quality can be used immediately for uses such as aquaculture, water sports and recreation, etc. Even partial remediation of highly acidic and saline waters can allow this water to be used for activities such as dust suppression, potentially reducing demands on other higher quality water sources (McCullough & Lund, 2006). However, despite the potential and existing examples of possible beneficial end uses for pit lakes, there are many pit lakes across the Australian continent with no planned end uses (Farrell, 1998).

The potential use of pit lake water remains dependent on the pit lake water quantity and quality (Doupé & Lymbery, 2005). However, there is no central database of existing or future pit lakes currently available in Australia. There has also been very little research on pit lakes in general with a detailed literature review for this chapter producing little information. What published information that is available is typically in the form of *ad hoc* opportunistic studies across a diverse range of disciplines including environmental engineering, geology, chemistry and aquatic ecology. Although many State and Federal primary industry and environmental agencies do collate mining data, including sometimes those of pit lakes and their characteristics, these data are generally limited to current or only recently decommissioned pit lakes. Many Australian pit lakes are on un-relinquished mining leases. This situation makes the long-term acquisition of data required to study the evolution of the quantity and quality of pit lake water a very challenging exercise. Furthermore, it is suspected that many pit lakes are considered commercially sensitive and are therefore not generally available for sampling and data collection. Such lack of detailed data of pit lake water quantity and quality for many regions currently renders it impossible to assess the risk and opportunities presented by pit lakes to Australia. Moreover, there are no guidelines for 'pit lakes' at the level of Federal government to be followed. In the Federal government's recent 'Mine Rehabilitation Handbook' guidelines (DITR, 2007) pit lakes are not mentioned.

1.5 Current study

Joint funded by the Department of Water, Western Australia and the Australian Government under its $12.9 billion Water for the Future plan, this project is focussed toward the management and use of pit lakes that have formed within the Collie Basin (the Collie Lakes District). The outcomes of this work are intended to support water resource planning and management in the Collie River catchment.

In late 2008, the Department of Water tendered a request for management of a research programme that would support and advise future water management in the Collie Basin in the south-west of Western Australia. A team lead by Edith Cowan University and comprising senior researchers from Mine Water and Environment Research Group (MiWER) and Centre for Ecosystem Management (CEM) at Edith Cowan University (ECU) and the School of Population Health, University of Western Australia (UWA) provided the successful tender for this research programme. This group of scientists have developed expertise in the area of environmental effects of mining over many years of specialist research and consultancy. Leading the mine water side of this research programme was Dr. C. D. McCullough, Associate

Professor Mark Lund with Dr Lu Zhao of MiWER (Mine Water and Environment Research Group). Dr. Andrea Hinwood, Dr. Jane Heyworth and Mrs. Helen Tanner contributed considerable experience on human health issues and epidemiology to the health component of Task 2. All staff involved were successful researchers who have significant experience and a growing publication record in the mine water and environment and health area. The combined experience of the research team is unique within Australia.

The research programme activities were expected to run from March 2009 to May 2010. Altogether, 5 tasks were part of this research programme including:

1. Developing an inventory of pit lakes' data including history, storage, hydrology, water quality, water source and ecology and preparing a summary report that includes a preliminary assessment of end-use options for each pit lake and highlights gaps in existing data sets;
2. An assessment of the current effects of pit lakes on human health;
3. Development of a monitoring strategy for pit lakes and connected waters with special attention to those of the Collie Lakes District;
4. Production of a report outlining conceptual models of Environmental risk assessment, ecological limitations and health and grouping Collie pit lakes with regard to their geo-hydrology; and,
5. Geo-chemical modelling of water chemistry within pit lakes under different management scenarios to support management decisions.

This report fulfils Task 3 of this Collie Pit Lake research programme by developing a monitoring strategy for pit lakes, particularly designed toward the requirements of data collection from pit lakes within the Collie Basin. These data include hydrology, water quality, water source and ecology. Recommendations are also given as to how this data is analysed and reported. Knowledge gaps in existing monitoring strategy recommendations are indicated and recommendations are made into the continuous refinement of an ongoing monitoring programme for the 15 lakes in the Collie Lake District.

The purpose of this document is to recommend state-of-the-art monitoring design and sampling methodologies for environmental monitoring of pit lakes and their immediate catchments in the Collie Lake District, south-western Australia. This report gives an overview of regional and international environmental issues related to pit lakes, current national guidelines and best practice international operations and recommendations for monitoring pit lakes aquatic ecosystems. The purpose of monitoring selected indicators and their field sampling and analysis methods and techniques are described, and the practical temporal and spatial issues targeting episodic events are discussed in detail. Strategies for data analysis and reporting are also suggested for maximising data value and for enabling during further strategy development during long-term monitoring. Based on these general principles of monitoring, quality assurance, health and safety and budget recommendations are included as well.

The water quality and other environmental legacies of pit lakes following completion of mining operations is one of the most significant environmental issues facing the mining industry. The Collie region now has a Lake District of 15 pit lakes from historic (*ca*. 1960) and current open-cut mining activities. The current demand for water in the south-west of WA and its increasing scarcity means that Collie pit lakes represent a potentially valuable resource to both the environment and the community. Many of these lakes represent poor water quality that cause risk to local and regional environments, yet conversely if treated this water could be of significant benefit to local communities if their environs are developed or managed to these end uses (McCullough *et al.*, 2010). As a result, a monitoring strategy for these pit lakes is required in order to achieve more stringent demands on pit lake conditions at relinquishment made by state and federal regulation and the desired end uses of local communities (McCullough *et al.*, 2009).

Targeting the environmental issues specific for pit lakes, this report is divided in three main parts:

1) Introduction to cover a review of the status and environmental issues of pit lakes, its related guidelines and the purpose of a monitoring strategy for pit lakes;

2) Discussion on monitoring water quality of pit lakes by applying the monitoring program, including objectives, water quality indicators, sampling and analysis quality assurance, health and safety and budget considerations.

3) Documentation and interpretation on the data obtained from a pit lake monitoring program, including data management and QA/QC, data analysis and assessment, programmatic evaluation and recommendations.

To obtain systematic water quality data of pit lakes incorporating hydro-geological, limnological, and biogeochemical processes, a monitoring strategy is needed. However, there are currently no Commonwealth, state or industry guidelines for monitoring lakes in lieu of better management and realisation of water resources. Internationally, a single brief chapter on broad guidelines has only recently been published in a US pit lake handbook that provides little guidance to development of a monitoring strategy for the purposes of particular lake types, regions and proposed end uses (Gammons, 2009).

This document is based on the experience of developing an inventory of Collie pit lake data and a preliminary assessment of existing dataset gaps (McCullough *et al.*, 2010). To support further water quality research, such as conceptual and numerical modelling, the design and recommendations of this water quality monitoring program will provide a good overview on historic and current parameter status and their predicted change and evolution. Also, the strategy report targets episodic events and gives short-term and long-term monitoring solutions, which will support water management and related decision making for pit lakes.

The intention of this work is, therefore, to develop and present *ad hoc* monitoring strategies for pit lakes, with particular regard for those of the south-west of Australia. This report attempts to answer these questions: “Why monitor water quality of pit lakes? How should a monitoring program designed? What needs to be measured and analysed, and how? How to report and interpret monitoring results?” This report should provide a solid reference for researchers to consider the investigations on pit lakes. It will also provide a useful overview of considerations and a generic approach useful for environmental officers in industry and governmental agencies with to arrange and process a practical monitoring project for pit lakes.

2 The Collie Coal Basin

2.1 Background

The town of Collie (population over 10,000) is located on the north western rim of the Collie coal basin within the Collie River catchment. Collie lies nearly 160km south-southeast of Perth, and is the centre of coal mining industry in Western Australia (Figure 4). The major land uses in the catchment are coal mining, timber production, power generation and agriculture. Approximately 79% of the catchment is state forest. The recreation and nature conservation values of the forest areas are highly regarded along with the recreational opportunities provided by the Wellington Reservoir and other surface waters, including some pit lakes. These values have led to increased promotion of the area for tourism by the local business community and the Shire of Collie.

2.2 Geology

The Collie Basin covers an area of approximately 224 km^2, 27 km long by 13 km wide and elongating in a north-west to south-east direction. The basin consists of two lobe-shaped sub-basins, the Cardiff sub-basin (151 km^2) to the west and the Premier sub-basin (74 km^2) to the east, in part separated by a faulted basement high, known as the Stockton Ridge (Moncrieff, 1993).

The Collie coal basin is a small sedimentary basin occurring in the Collie River catchment (Figure 4; (CWAG, 1996)). The Basin contains up to 1400 m of Permian sedimentary rocks, covered by a thin layer of Cretaceous rocks. The base layer of pebbly mudstone is covered by layers of sandstone, shale and coal. There are up to 55 significant coal seams which are typically 1.5 to 5 m thick although the Hebe seam reaches 13 m thick glacial sediments and coal measures. There are an estimated 1,330 Mt of coal resource in the basin of which extractable reserves account for 480 Mt (Varma, 2002).

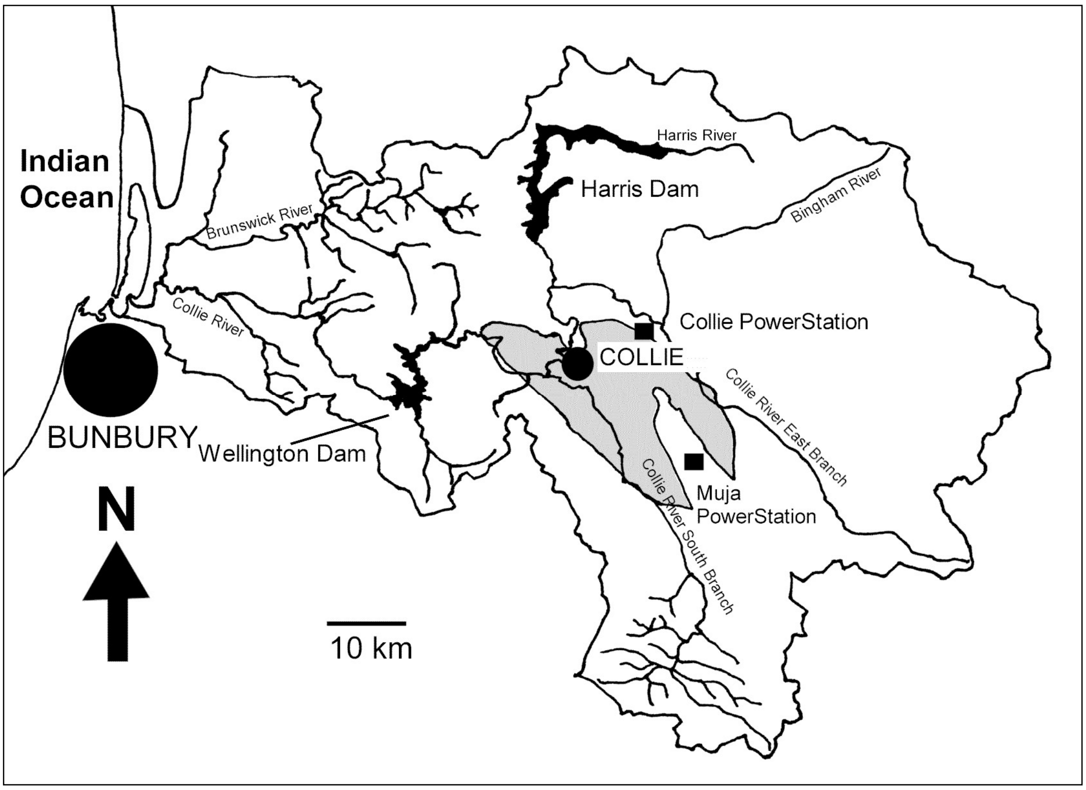

Figure 4. Location of the Collie Basin (after Neil *et al.* 2009).

2.3 Climate

Collie is located in the south-west of Western Australia. Collie is situated in an area of Mediterranean climate, with hot, dry summers (range 12-29°C) and cool, wet winters (range 4-15°C) (Commonwealth of Australia Bureau of Meteorology, 25/02/2009). Seventy-five percent of rainfall occurs in the five months from May to September (Figure 5). The 100 year mean annual rainfall for the Collie Basin is 939 mm, (Commonwealth of Australia Bureau of Meteorology, 25/02/2009) although this has decreased to an average of 690-840 mm over the past 20 years (Craven, 2003).

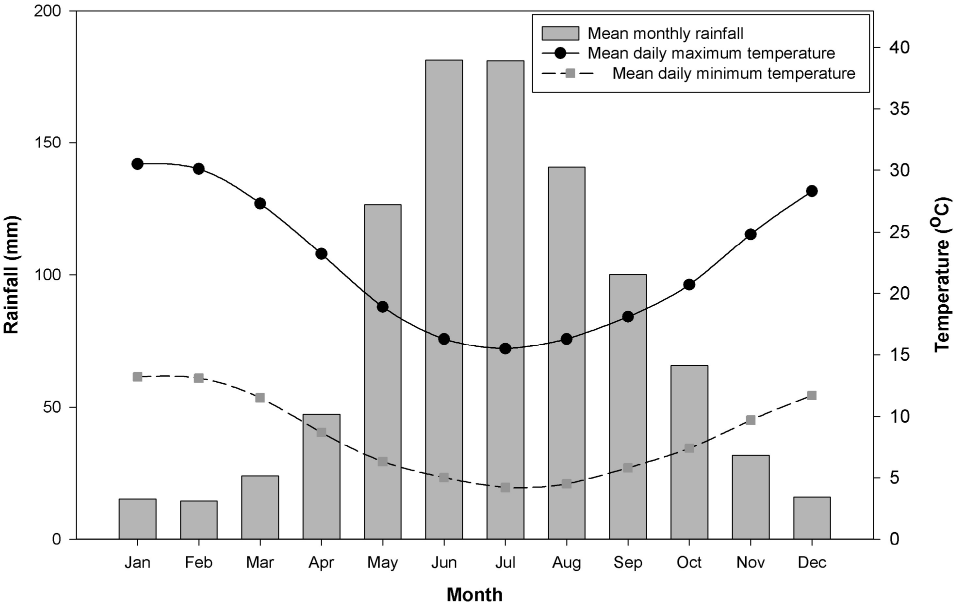

Figure 5. Mean temperature and rainfall climate of Collie (Commonwealth of Australia Bureau of Meteorology, 05/10/2005).

2.4 Groundwater

Groundwater resources of the Collie basin are fresh and discharge towards the Collie River, with seasonal fluctuations up to 1 m (Sappal *et al.*, 2000). The pH of groundwater is highly variable ranging from <4 to neutral (Varma, 2002).

Groundwater (in abstractable quantities) in the Collie basin is mainly contained within the sandstone of the Muja Coal Measures, Premier Coal Measures, Allanson Sandstone, Ewington Coal Measures and Westralia Sandstone of the Collie Group; within the sand and sandstone of the Nakina Formation; and in the surficial sediments (Varma, 2002). The hydrogeology of the Collie basin is complex, with multiple aquifers as a result of aquicludes and faulting (Varma, 2002).

2.5 Collie River

The Collie River is the main river system of the Collie basin, running almost 100 km westward to the Indian Ocean. It was once fresh but due to clearing of the upper catchment for agriculture, the salinity has risen to over 1000 mg L^{-1} (Mauger *et al.*, 2001). It is also now eutrophic, with total phosphorus levels were recorded at over 18 µg L^{-1} (Salmon, UWA, unpublished data). The south branch of the river was diverted around the former WO5B (Lake Kepwari) mine pit during operations and has been used to fill the void when winter flows were sufficient.

Wellington Reservoir was built on the Collie river, 35 km from the Collie townsite, in 1933 as a source for irrigation for the coastal plain (Mauger *et al.*, 2001). The dam was raised to its current capacity of 185 GL in 1960 and used for drinking water. Rising salinity in the river meant the dam was no longer suitable for drinking water and was replaced in this capacity by the Harris dam in 1989 (Mauger *et al.*, 2001).

2.6 Mining in Collie

Underground and open cut coal mining has taken place in the Collie basin since 1898. Until the mid 1990’s coal mining was predominantly in the Cardiff sub-basin. In 1997 mining in the Cardiff sub-basin ceased and since then mining has taken place in the Premier sub-basin at the Muja, Ewington and Premier mines. The history of Collie coal mining is detailed in Stedman (1988). As a result of a dispute with the Government, six open cut pits were abandoned in 1950s and 1960s, which went on to form Stockton Lake, Ewington Lake, Blue Waters, Black Diamond (A & B) and Wallsend (used for landfill) (Figure 6).

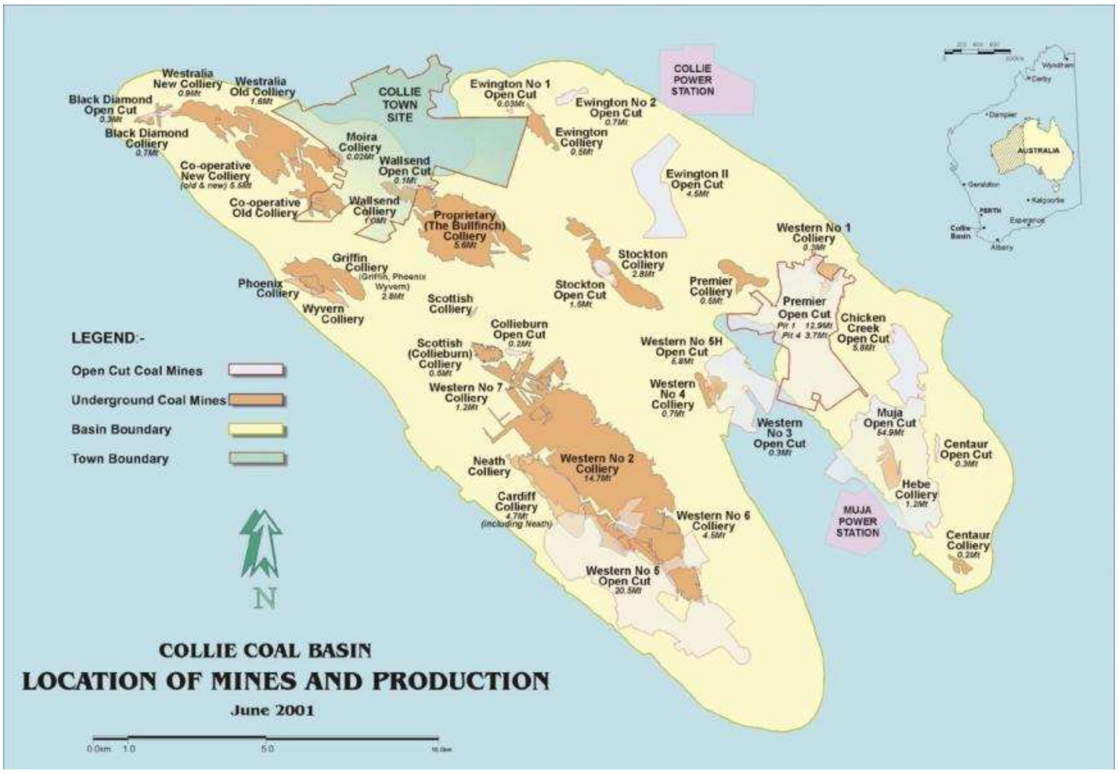

Figure 6. Historical mine workings in the Collie Basin (source unknown).

Currently two mining companies (Wesfarmers Premier Coal Pty Ltd and Griffin Coal Pty Ltd) have active mines in the Premier sub-basin. Wesfarmers Premier Coal Pty Ltd is currently rehabilitating or developing end uses for finished pits in the Cardiff sub-basin (Figure 7).

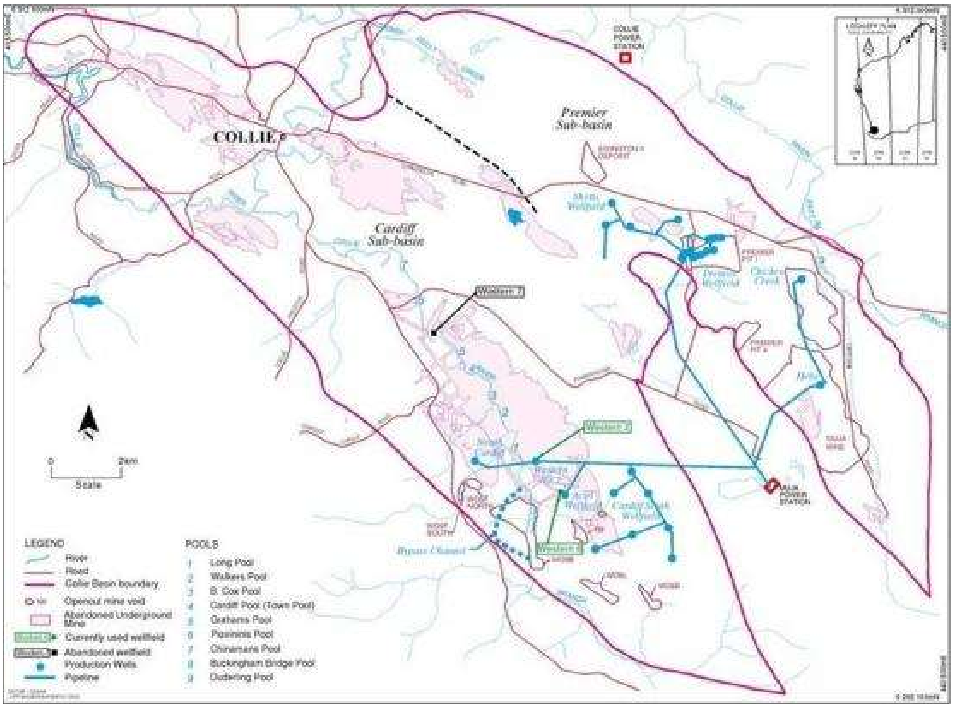

Figure 7. Current mining activities in the Collie Basin (source unknown).

2.7 Collie Pit Lakes

There are currently 13 mine pit lakes in Collie, with surface areas ranging between 1–10 ha, depth between 10–70 m, age between 1–50 years and pH 2.4–6.8 (Figure 8). Water quality of pit lakes of Collie is degraded by AMD, mainly in terms of low pH and elevated concentrations of selected metals.

Collie black coal has low sulphur concentrations (0.3–1%) (Le Blanc Smith, 1993) and only produces low amounts of acidity through pyrite oxidation, ferrolysis and secondary mineralization. This low acidity is still sufficient to generate low pH in pit lakes due to low buffering capacity of surrounding geologies. These pit lakes also have very low nutrient concentrations of carbon, particularly in historic lakes where it may be at detection level of <1 mg L^{-1} (McCullough *et al.*, 2010). The few ecological studies made on Collie pit lakes highlight nutrient limitation restricting algal productivity and hence lake foodwebs (Lund *et al.*, 2000; Lund *et al.*, 2006; Thomas & John, 2006; Salmon *et al.*, 2008).

Figure 8. Location of current Collie pit lakes (sourced from Google Earth). Note: Wellington Dam is a reservoir.

3 Designing a monitoring program

3.1 Monitoring

3.1.1 Why monitor?

Pit lakes are both potential water resources and potential environmental risks and, as such, raise significant environmental issues for the mining industry. Increased social expectation, including legislation and other regulation and desired end uses by local communities, are increasingly requiring higher standards of environmental assessment and management for pit lakes (Jones & McCullough, 2011).

In practice, monitoring requirements may be imposed for compliance through regulatory authorities to prevent or mitigate environmental impacts and to facilitate improvement of environmental and social performance indicators after mining operations have ceased. Mining companies may also desire elevated monitoring requires as a demonstrable measure of corporate responsibility to the local community and to their stakeholders such as shareholders of sustainable mining operation and environmental performance. Pit lake water quality monitoring may also be requested by surrounding communities who are interested in understanding if there are or will remain any environmental impacts of mining operation and whether they are able to safely use the pit lakes as resource e.g., for recreation.

3.1.2 Monitoring strategy

Monitoring pit lakes is the process of routinely, systematically and purposefully gathering information for use in management-decision making (Verburg *et al.*, 2009). Monitoring should include qualitative data observations, such as recording information about the pit lake environment. Monitoring may also be extended into *ad hoc* investigations, such as analysis of toxic effects of pit lake water on biological communities such as bioaccumulation studies may also be required (Ribaa *et al.*, 2005). Although they should be specific to the purpose they are being established for, fundamentally, the underlying goals of monitoring information obtained from the pit lake monitoring programs are typically to protect human health and assess environmental risks.

In theory, monitoring strategies for pit lakes are not much different from monitoring a natural lake. However, due to frequent dissimilarities in the physical, chemical and biological characteristics of pit lakes and their catchments, and the different and often significant risks these characteristics present, it is necessary to adapt these general lake monitoring principles to suit.

Monitoring pit lakes should also include general observations such as records of information about the pit lake and surrounding environment appearance such as water colour, changed landscape features such as slips and erosion, and fire and other activities.

3.1.3 Monitoring data for modelling

As a key component of mine closure, pit lake monitoring can establish current (e.g., baseline) conditions and current trends, provide information for modelling prediction and help better understand pit lake ecosystem development and limitation. These data will consequently help decision makers achieve better closure practice and to realise potential end uses, such as recommendations of possible remediation approaches or treatment methods and what closure goals are achievable following these. There are several modelling strategies for mine lakes, hydrological modelling focusing on the input and discharge of ground water and surface water (Niccoli, 2009); physical limnology modelling on pit lake stratification and circulation (Hamblin *et al.*, 1999; Castendyk & Webster-Brown, 2007); geochemical modelling on pit lake geochemistry and water quality (Eary, 1999); and biological modelling on ecological community structure (Kalin *et al.*, 2001; Jin & Bethke, 2005). A significant level of detail within the pit lake and often also its surrounding catchment may be needed to produce accurate results for modelling prediction in these disciplines.

Water quality in a pit lake is determined by the varying proportions and chemistry of both groundwater and surface water sources flowing into the pit lake combined with internal geochemical processes and physical limnological processes in the pit lake. Therefore, monitoring pit lake quality also requires monitoring of fundamental hydro-geological, limnological, and biogeochemical processes.

Climate (temperature, precipitation, runoff, evaporation and wind), lake morphometry (depth, volume and catchment area), and the volume and chemistry of groundwater and surface water fluxes are required often required as background information. These data can be collected as a single event when the lake environment has stabilised e.g., when the lake has filled, or more frequently if the pit lake environment is changing rapidly e.g., during filling or following intended/unintended intervention such as unexpected climatic events.

Nutrient concentrations (N, P and C) and their fractions play an important role in determining the pit lake's ecological character with respect to productivity and biotic assemblages present or able to survive. As macro-nutrients, concentrations of these elements may change rapidly over time as they are consumed/excreted and modified into different forms. Typically, phosphorus will be considered as total (and soluble (not bound; biologically available) concentrations. Nitrogen will be separated into total (often as Kjeldahl's) and NO_2/NO_3 (as NOx) and the ammonia/ammonium equilibrium as ammoniacal nitrogen. Because nutrient are readily biological available, their concentrations can change over a sort period of time , with these changes correlating with abiotic causative factors to the lake's biota such as season as temperature and light availability.

Metal and other elemental concentrations are typically the main concern for water quality in pit lakes. Whereas some metals are essential for ecological development (e.g., Ca, Mg and K), some metals may contribute to acidity and buffer of pH increase (i.e., Fe, Mn and Al) and toxic trace metals may be of concern for human health and aquatic ecosystems (e.g., heavy metals such as Cd, Ni, etc.).

Changing conditions over lake depth, such as the levels of dissolved oxygen, carbon dioxide, salinity, total dissolved solids (TDS), pH and redox potential, either due to gradients or sudden changes as thermo-/haloclines, also need to be measured with greater spatial sampling frequency.

However, in recent work of the Mine Water and Environment Research Group (MiWER), based at Edith Cowan University, Western Australia, a pit lake water quality database was compiled (McCullough *et al.*, 2010). During this exercise, data were collated from a number of sources including research institutions, government agencies and mining companies. Much of the compliance mining data included only partially filled pit lake water quality data and pit lake characteristics and all was limited to only recently decommissioned pit lakes. Because the data was collected by various purposes, such as drainage or engineering operations, important water quality parameters were often missed. Such lack of detailed and systematic data of pit lake water quality is, however, all too common for other mining regions in Australia, and renders it impossible to assess the risk and opportunities presented by the water quality of pit lakes to their regions (Kumar *et al.*, 2009). Such a lack of systematically collected relevant and qualified water quality data has been identified as one of the primary limitations to understanding and management of the Collie Lake District resource (McCullough *et al.*, 2010). This paucity of data reduces the understanding of how pit lake sevolve overt time including modelling prediction ability.

3.2 Relevant monitoring protocols and standards

Also specific guidance may still be absent from the literature, there are general mine and lake water quality monitoring protocols and standards available which can help guide pit lake water quality management and monitoring (Table 1). The International Network for Acid Prevention (INAP) has produced a global acid rock drainage (ARD) guide (GARD Guide) which summarizes the technical and management practices for industry and stakeholder use (Verburg *et al.*, 2009). There are also many scientific and technical organizations working on ARD and heavy metal pollution in mine operations, such as the International Network for Acid Prevention (INAP), Mine Environment Neutral Drainage (MEND), the International Mine Water Association (IMWA), the Acid Drainage Technology Initiative (ADTI), the Australian Centre for Minerals Extension and Research (ACMER), the South African Water Research Commission (WRC), and the Partnership for Acid Drainage Remediation in Europe (PADRE). These organisations have all published guidelines which, together, represent an overview of strategies on monitoring water quality of surface water relevant to mining industries from international and national level of governments and organizations. All these sources' strategies may provide general guidance for monitoring mine waters, however, they all are deficient on the specialised advice required for monitoring pit lake water quality although they provide the references on monitoring water quality of pit lakes in this document. Selection of related guidelines and appropriate sampling protocols will depend on the site specific characteristics, permitting standard limits and requirements and required data accuracy and precision.

Table 1. Guidance and protocols, and standards related to pit lake water quality management and monitoring.

Guidance reference	Author	Overview
ANZECC/ARMCANZ (2000a) – Australian and New Zealand Guidelines for Fresh and Marine Water Quality	Australian and New Zealand Environment and Conservation Council/Agriculture and Resource Management Council of Australian and New Zealand	ANZECC (2000) provides detailed guidance on water quality data analysis options, including a recommended approach for comparing monitoring data with trigger values. ANZECC (2000) gives guidance for practice surface water quality management with a complete outline for aquatic ecosystems, primary industries and human health and an extensive discussion of the underpinning science. Also provides Commonwealth limits and trigger values for stress factors and pollutants in water body for various standard end uses. Water quality monitoring reporting for pit lakes are advised to use these guidelines to meet various end user requirements.
ACMER - A guide to the application of the ANZECC/ARMCANZ water quality guidelines in the minerals industry	Australian Centre for Mining Environmental Research (ACMER)	Written specifically for the minerals industry to understand ANZECC/ARMCANZ (2000a) guidelines and apply them to mining operations. A simplified form that only includes basic information and descriptions. Explains relevant trigger values and management framework and provides general information on monitoring mine water and assessing sediments, groundwater and biological parameters.
GARD - The Global Acid Rock Drainage Guide	International Network for Acid Prevention (INAP)	Consolidates relevant information and summarized the technical and management practices for industry and stakeholder use. It also provides a structured system to indentify proven techniques for characterization, prediction, monitoring, treatment, prevention and management of AMD (Verburg *et al.*, 2009).
ADTI - The Acid Drainage	ADTI is a government/industry	ADTI is a technology development program, addressing drainage quality issues from

Guidance reference	**Author**	**Overview**
Technology Initiative	joint venture in USA.	abandoned, active, and future coal and metal mines and focusing on mine drainage prediction, sampling/monitoring, modelling and avoidance/remediation, mitigation and pit lakes. It identifies, evaluates and develops cost-effective and practical acid drainage technologies including drainage quality issues related to metal mines.
PIRAMID - Engineering guidelines for the passive remediation of acidic and /or metalliferous mine drainage and similar wastewaters' (2003)	European Commission - Research and Technological Development project, the 5th RTD Framework Programme: PIRAMID (Passive In-situ Remediation of Acidic Mine/Industrial Drainage)	Focused on sustainable management and quality of water PIRAMID provides a basis for developing and implementing robust engineering designs for the passive treatment and /or passive prevention of mine water pollution and specifies the detailed civil engineering techniques, such as artificial wetlands and subsurface-reactive barriers.
ERMITE - Environmental Regulation of Mine Waters in the European Union (Anonymous, 2004)	European Commission - the 5th RTD Framework Programme: ERMITE (Environmental Regulation of Mine Waters in the European Union)	Provides integrated policy guidelines for developing European legislation and practice in relation to water management in the mining sector. ERMITE addresses various regional and national conditions in EU Member States and some Eastern Europe countries involved in the EU process and it integrates different disciplines: water resources, mining, ecology, economy, law, institutions and policy.
USGS – National field manual for the collection of water-quality data: U.S. Geological Survey Techniques of Water-Resources	U.S. Geological Survey	As part of its broad mandate, the USGS also provides resources for water resource management in USA to collect data describing the physical, chemical, and biological attributes of water systems accurately. Used for environmental assessments by USGS, other government agencies and scientific organizations, and the general

Guidance reference	Author	Overview
Investigations (U.S Geological Survey, Jan, 2010)		public.
Snapshot of Lake Water Quality in New Zealand (2006)	Ministry for the Environment	Identifies 153 New Zealand lakes monitored for trophic status, ecological condition or cyanobacteria through monitoring programmes, reports on monitoring techniques and provides a national summary of monitoring results. Gives examples of biological and ecological monitoring and assessing lake water quality in lakes.
Creating lakes from open pit mines: processes and considerations, with emphasis on northern environments	Canadian Technical Report for Fisheries and Aquatic Sciences 2826	Summarises the literature of mining pit lakes (through 2007), with particular focus on issues that are likely to be of special relevance to the creation and management of pit lakes in northern climates. The management end use strategies, such as swimming and water skiing, can be directly relevant to recreation activities in Collie pit lakes.

Like any other environmental monitoring design, the development of a monitoring strategy for pit lake environs primarily depends on firstly a clear statement of the objectives of the monitoring exercise. The monitoring strategy should target episodic events and develop a process of routinely, systematically and purposefully gathering information to serve different purpose, such as characterization of current conditions (baseline investigation) and natural variability, providing data for risk modelling prediction, assessment of the risks on human health and environment, and the use in management-decision making by the compliance of regulatory authorities, mining industries and surrounding communities (Figure 5).

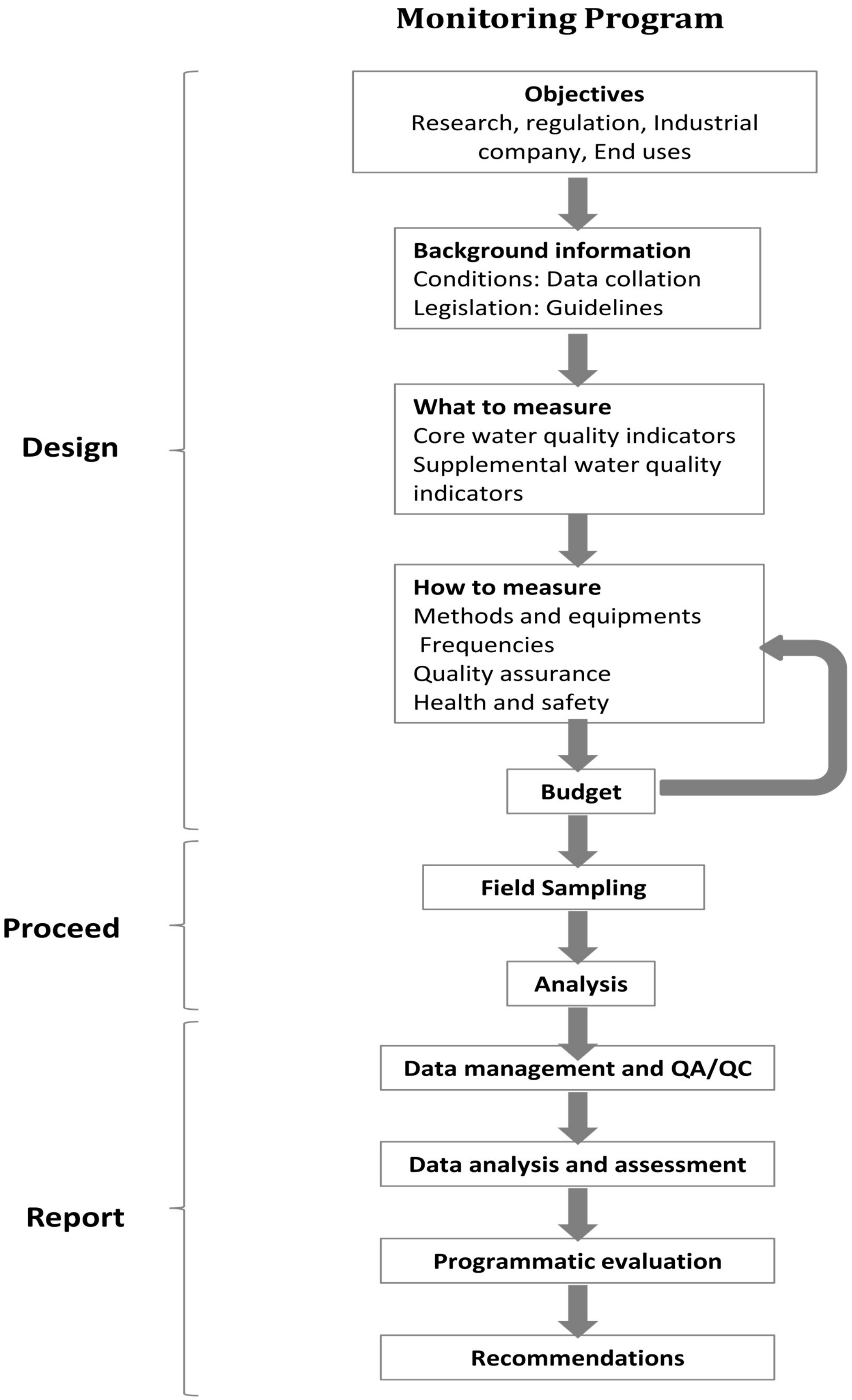

Figure 9. Suggested development strategy for a pit lake monitoring program.

3.3 Defining monitoring objectives

A monitoring project can be assigned by governmental agencies, industrial companies or local communities. It can also be part of research interests or modelling needs where the requirements of a monitoring project for water quality of pit lakes may differ in scale, precision and focal points. However, the very first step in developing a monitoring project is to define monitoring objectives. These objectives decide what to sample and measure in pit lakes.

3.3.1.1 Collation of existing data

Based upon these established objectives, existing data of targeted pit lake should first be collated. Historical data can greatly enhance existing datasets by informing of biological and physico-chemical trends and can often be obtained from mining companies, research institutions and government agencies. However, due to the diversity of objectives in disparate studies, these data may not cover all the needed physio-chemical parameters. Pit dewatering data (not pit lake proper) may not be relevant since the pit lake conditions are still rapidly developing. Regular QA/QC will also need to be carefully carried out. For example, inconsistent units in data or data with different sampling methods may need to be re-calculated where possible. Some data, often found in operational water quality datasets, have no relevance to the water quality, such as pumping water data for power stations during mining operations.

Existing information may also include climate, geology, hydrology, geochemistry and ecology data. Such information can be retrieved from local weather reporting agencies, research institutions and industry itself. Use of these established data collection sources for other purposes may assist the monitoring program in adjusting scale and points of focus as a means of reducing and refining monitoring program expenses.

Nonetheless, although historical data are useful and may form a significant component to a monitoring dataset, monitoring water quality of pit lakes after mining operation ceases should be considered a long-term process. To understand the process of lake development, identify the potential risk to human and environment and provide remediation for possible end uses, a variety of information still needs to be carefully collated from a variety of aspects of pit lake character and over a significant duration of time.

3.3.1.2 Defining the monitoring situation for pit lakes

Australasia's primary water quality guidelines ANZECC/ARMCANZ (2000b), gives a complete outline for aquatic ecosystems, primary industries, human health values, while with lengthy discussion of the underpinning science. After determining appropriate toxicant trigger values from the guideline, further site-specific investigations are needed, which requires consideration effects of local ecosystems and comparison with local reference conditions, for example, public access and social needs, economic development and special ecological conservation requests.

However, since each pit lake has its own peculiar characteristics, it is very difficult to make universally valid recommendations. Nevertheless, by reviewing guideline and analysis of existing water quality data, it is possible to characterize pit lakes into categories. For instance, historic lakes may not continue to significantly evolve annually in term of water quality and lake morphology while only seasonal changes and climate changes play a primary role in their developing trends. Conversely, newly developed lakes may develop each year through much greater changes in water depth and water quality by the initial geochemical reactions between water and sediment and wall rock. According to the public access and end user's interests, the emphasis of reclamation of pit lakes can be different, for example, high concentrations of metals may affect fisheries; low pH imposes a health risk for water sports and both may be considered significant health risks for drinking water by humans and animals.

3.4 Developing a monitoring strategy

The development of a pit lake sampling plan is the first and most important step in a pit lake monitoring project. A clear and careful plan is a foundation to guide the sampling actions running smoothly and efficient with the limited budget time. A sampling plan should be written in as much detail as possible and peer-reviewed to make sure the coverage of necessary measurements and practical experiences. The plan should include at least the following components:

1) Project objectives.
2) Personnel involved and their contact information.
3) Timelines, relevant maps and required routines.
4) A checklist of equipment and supplies.
5) List of sample types required at each location.
6) List of quality assurance samples, such as duplicate samples, blank samples and split samples for different laboratory tests.
7) Standard preparation procedures for calibration of equipment, bottle rinsing and filtration, acid preservation and other decontamination procedures.
8) Sample containers (bottles and filters) and labels.
9) List of physical and chemical parameters to be quantified.
10) List of laboratory methods required, and what instrument detection limits are needed.
11) Conditions required for sample preservation, exposure temperatures and storage time limits.
12) A protocol for use of chain-of-custody forms.
13) A plan for managing Health and Safety plan in the field and laboratory.

3.4.1 How to sample

Theoretically, retrieval of water samples from mining pit lakes is no different than collecting water samples from any deep lake. However, in practice there are many special characteristics of pit lakes which need to be considered. Pit lakes are typically much steeper and deeper than natural lakes, with wind fetch across their surface further reduced by the presence of over-burden and waste rock dumps (Huber *et al.*, 2008b). It is important to measure temperature and pH of water samples in situ to evaluate such stratification effects. Consequently, surface water samples may not represent those of the greater water column and some depth point sampler, such as a van Dorn or Kemmerer sampler may be required (Plate 2). And it is better to obtain temperature and pH of water samples *in situ* using a submersible multi-probe, since temperature may change quickly as water samples are raised to the surface and dissolved gases (such as CO_2) may separate out due to the drop in pressure.

Plate 2. Kemmerer bottle sampling low redox hypolimnion waters of an acidic North Queensland pit lake.

3.4.2 When to sample

The sampling frequency for a given pit lake will firstly depend on availability of funds and regulatory requirements such as Ministerial Statements and compliance reporting. However, a vertical profile of water samples for complete chemical analysis should be collected once a year at least. If a seasonal climate is obvious, seasonal sampling may first establish inter-seasonal variability e.g., winter and summer sampling four times a year or dry and wet season sampling at least twice. Sampling should take place near the end of each season to capture that season's water quality changes.

A change of volume or composition of influent waters may also require more frequent sampling. For more frequent sampling, installation of a vertical array of CTD sensors to continuously record temperature and conductivity information over an entire calendar year may be a good option to track seasonal changes in the depth of the thermocline or chemocline, which provides information on pit lake turnover.

3.4.3 Where to sample

Collecting pit lake samples requires consideration of both lake surface location as well as water column depth. In terms of lake surface location, it is best to collect samples above the deepest part of the lake to avoid missing a deep layer of water where stratification occurs. Groundwater may also be more pronounced at such locations e.g., as a monimolimnion which may have been otherwise missed by sampling shallower locations (Boehrer & Schultze, 2006). By using geographic coordinates or a buoy as a guide, collecting samples at the same location each time is optimal for direct comparability and trend analysis between different sampling event times.

In term of depth, a conductivity-temperature-depth (CTD) profile and the total lake depth may be needed before retrieving water samples. The results of the CTD profile can show the presence of any thermal or chemical boundary layers as thermoclines and chemoclines respectively. The number of water samples will then depend on the complexity of the CTD profile and the number of strata identified. For example, a simple stratified lake with a surface layer (epilimnion) and bottom layer (hypolimnion) monitoring would only require two water samples, one from each layer to be collected. Three or five water samples may even be enough to characterize vertical gradients for monitoring purposes, depending on the total depth of lake.

It is also important to collect samples of any influent water entering pit lakes. Such information is essential for mass balance of water chemistry, such as salinity. Diffuse groundwater input can only be approximated by knowledge of ground water pumping rates before mining cessation. The volume and chemical composition of groundwater springs, adit discharges and permanent or transient surface water can be sampled and quantified. Runoff from the mine wall after a major rain event, especially the first rain after an extended dry period may be also worth sampling for prediction of water chemistry (Morin & Hutt, 2001).

4 Key water quality indicators

The principal monitoring target of pit lakes is the lake water body itself, and most importantly water quality including measurements of depth, water temperature, conductivity, pH, dissolved oxygen (DO), turbidity and light attenuation. Other chemical parameters including total and dissolved metals and metalloids, major anions and nutrients and buffering capacity will also be key data as these will inform any established water quality compliance and standards. Biological parameters are also important and include aquatic macroinvertebrates, zooplankton, periphytic algae, crayfish, finfish, phytoplankton biomass (as chlorophyll-a) and aquatic macrophytes.

Nevertheless, as illustrated by the general conceptual model of pit lake water quality drivers (Figure 1), there are many variables from the surrounds of the pit lake water body that also must be considered. These variables include input and output of water and chemicals to the pit lake, such as through surface and ground. Also important to pit lake water quality and ecology will be the inputs of nutrients and metals from riparian plants and soils in the catchment area and by sediment flux within the lake itself.

With such a board range of variables to monitor from, the monitoring program design must clearly indentify potential pit lake end uses. Whilst some monitoring variables will be general and provide parameters for many end uses, for example pH for swimming and ecological value, other variables such as bacteria for drinking water may require more specialised monitoring programme design and attention.

Key recommended water quality indicators are discussed thoroughly in this section and other water quality indicators are covered as well. However, general ideas such as know the parameters to be sampled in the monitoring program, the planning of access and transport to and from the study site and considerations about health and safety issues are also discussed.

4.1 What to sample for

4.1.1.1 Metadata

Metadata (i.e., data about data) such as the date, time, Global Positioning System (GPS) location and climate information are general information that should always be recorded for all samples along with water quality variables. The date of samples can give the information about the seasonal and annual changes. Some variables may also be sensitive to daylight, such as pH and DO so a record of sampling time can help explain these differences when analysing monitoring data. GPS coordinates are useful for explaining spatial differences in data and to test if a consistent same sample site has been used, thus explaining data variations simply due to sampling inconsistent locations.

4.1.2 Field physico-chemistry

Field measurements are used to determine physico-chemical and biotic properties onsite, as close as possible in time and space to the media being sampled (Wilde, 2005). Some measurements can be rapidly recorded *in situ*, such as temperature, depth and light, which are important information for latter calibration and adjustment of laboratory measurements. There are measurements which have to be quantified immediately because of the effects by the disturbance of temperature and pressure, such as conductivity, dissolved oxygen and redox status.

Water parameters here include physical and chemical characteristics which can be measured directly *in situ*. These measurements can be carried out in a rather short time with combination instruments.

4.1.2.1 Water temperature, and conductivity

Conductivity, Total Dissolved Solids (TDS) and salinity are all measures of water electrical conductivity. Electrical conductivity (often simply called EC) and temperature are two useful parameters to monitor in a pit lake in order to estimate lake water salinity and density. These parameters are critical to determine a given lake is likely to turn over annually (holomictic) or permanently stratified (meromictic). Since the two parameters often change over depth, these three parameters have to be measured *in situ* at the same time. Since conductivity of water increases rapidly with temperature, the reported conductivity values need to be corrected to a reference temperature. This correction is typically made to standard temperature of 25ºC as is then reported as "specific conductivity" (SC25).

A submersible multi-parameter meter is often used to measure and record temperature and conductivity continuously together with water depth measured by an integrated pressure sensor. Depending on the parameters required, other probes, such as pH, DO, Eh and turbidity can also be fitted to the sondes and their measurements recorded simultaneously. A specialised very long meter cable and depth metering capacity may be required as pit lakes are typically very deep more than e.g., 50 m. It is also essential to have a budget in the monitoring project for regular maintenance work to regularly inspect and replace any defective probes. It is also very important to the life-span and accuracy of the instruments that probes are cleaned after use and stored following the manufacturing instructions. To this end clear record keeping of calibration and maintenance for each instrument is also a requirement.

Plate 3. The datasonde 4a, an example of a multiparameter meter made by Hydrolab (Austin, USA).

4.1.2.2 pH

The pH must be determined *in situ* as well as at all depths where any pit lake water samples are collected. Dissolved gases such as CO_2 in water are sensitive to the changes of temperature and pressure and influence pH measurement. The chemical balance of dissolved Fe and sulphate is also temperature-dependent and may affect pH determination.

A convenient way to measure pit lake pH in the field is to combine an electrode probe into a multi-parameter meter and record pH together with CTD data. A calibration of pH is needed before field measurements and the calibration range required will depend on the lake pH range expected (e.g., acidic pH 4-7 or alkaline pH 7-10).

4.1.2.3 Dissolved oxygen and oxidation-reduction potential (ORP/Eh)

The redox status of water controls the circles of nutrient elements which is the foundation of ecological community of pit lakes. It is also important since the fate and transport of trace metals and other contaminants changes dramatically depending on the redox conditions of water. Dissolved oxygen (DO) and oxidation-reduction potential (ORP/Eh) measurements characterize the redox state of water. The concentration of DO is highly dependent on temperature, salinity, biological activity (microbial respiration and primary production) and rate of transfer from the atmosphere. Under natural conditions, DO may vary diurnally and can become depleted in DO, particularly when the systems are stratified. DO has to be carefully monitored when loading biodegradable organic matter as an approach to remediate pit lakes, since it is possible that organic matter degradation may exhaust DO and change the redox status of water column and consequently change the biogeochemistry of water.

The ANZECC/ARMCANZ guidelines (2000a) recommend default trigger values for physical and chemical stressors of freshwater lakes and reservoirs for dissolved oxygen should be about 90–110% saturation for south-east Australia, 90–120% for tropical Australia, and a 90% lower limit for south-west Australia. As a precautionary approach, DO concentrations may be obtained from daytime measurements when they will be expected to be at their lowest following respiration overnight in the absence of photosynthetic activity. DO measurements should also be taken from undisturbed waters and at highest temperature periods when DO is likely to be at their lowest.

If a pit lake is rather new and still in the formation process of a lake, an appropriate site-specific study of water characteristics should be made. Dependent upon available information, a desired level of protection for the ecosystems should be decided by professional judgement, which will then determine if regular monitor measurement for DO is necessary.

DO electrodes can also be fitted into multi-parameter meters and recorded with depths simultaneously with other parameters.

4.1.2.4 Turbidity or Total Suspended Solids (TSS)

The distribution of particulate matter through water column shows gravitational settling of solid particles for a given pit lake. Waters with high TSS may have higher density than the value predicted from SC25 (specific conductance) and temperature alone and this has implication for modelling of water column mixing. Elevated TSS is often found as a consequence of mill tailings or sludge resulting from lime treatment that are comprised of predominantly fine particles, or from erosion of pit banks and surrounding un-rehabilitated pit lake catchment, particularly after heavy rainfall (Plate 4). TSS strongly influences light penetration and consequently influences biological productivity.

TSS can be obtained by filtering a known volume of water and then weighing the residual dried solid. The used filter papers from the TSS measurements can also be stored for later mineralogical or geochemical analysis of the suspended particles. Alternatively, a turbidity sensor (often mounted in a multi-parameter probe) can be used in situ to obtain detailed turbidity profiles with depth by collecting turbidity data from light scattering properties of water as Nephelometric turbidity units (NTU). A strong correlation can often be established between TSS and turbidity in a subset of samples.

The ANZECC/ARMCANZ guidelines (2000a) recommend a range of default trigger values for physical and chemical stressors of freshwater lakes and reservoirs. However, only turbidity is reported since TSS is typically strongly correlated with turbidity. ANZECC/ARMCANZ guidelines are for 1–20 NTU for south-east Australia, 2–200 NTU for tropical Australia, and 10–100 NTU for south-west Australia. These latter values should be therefore used in Collie pit lakes. In general, deep lakes are expected to have lower turbidity and shallow lakes may have higher turbidity naturally due to wind-induced re-suspension of sediments. If catchments contain highly dispersible soils such as clays, lakes may also have high turbidity. If a significant surface water system drains into lakes, high turbidity may also be expected.

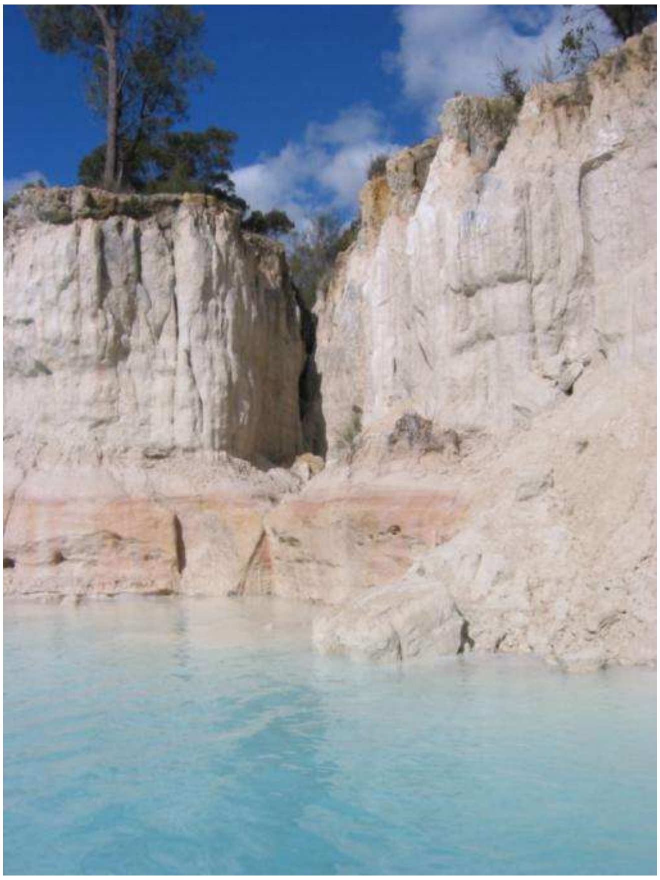

Plate 4. Bank erosion in Blue Waters Lake which may lead to elevated water turbidity.

4.1.2.5 Water colour and appearance

Water colour is an important optical property for pit lakes, especially for monitoring towards desired end uses. However, colour is not often used in data reporting of water quality.

Colour is also an important water quality characteristic for recreational use. Considering this aesthetic quality, the natural visual clarity should not be reduced by more than 20%, the natural hue of the water should not be changed by more than 10 points on the Munsell Scale and the natural reflectance of the water should not be changed by more than 50%. To best offer a visual clarity of waters useful for swimming, the horizontal sighting distance of a 200 mm diameter black disc should exceed 1.6 m.

Colour data should be consistently collected, reported and used to match colour changes to chemical parameters of lake water. For example, colour can be a useful indicator of redox state for pit lakes, especially Fe-rich, acidic lakes. Using established standards such as Munsell colour charts can minimize the subjectivity of observations.

4.1.2.6 Light attenuation

Light attenuation is a limiting factor for algae growth which affects the primary production as carbon dioxide absorption by plants and algae of a water body. Suspended particulate matter can increase light attenuation into a water body and result in reduced primary production. The presence of light-absorbing compounds in the water, such as ferric iron, may also increase light attenuation rates. Using a Secchi disk is a simple way to measure light penetration and the results are called Secchi depth. A more relevant and accurate method is to use paired photosynthetic available radiation (PAR) meters at the surface and along a depth profile to derive a coefficient of attenuation constant for the lake as Kd (PAR).

The ANZECC/ARMCANZ guidelines (2000a) recommend a lake's light climate as a recommended biological indicator for which there is not recommendation available, but for which data collection can be developed relatively quickly with additional resourcing. There is a move towards the measurement of light attenuation in preference to turbidity in lakes. Light attenuation can be a good reference as the water system in new pit lakes is often not stable due to the ongoing input of turbid water from the catchment or surface water rapid filling such as from river diversions. Light attenuation data is not required for Collie River monitoring.

4.2 Laboratory solute analysis

Analysis of chemical solutes include the chemical measurements which are carried out in an analytical chemistry laboratory. These variables give basic information on possible pollutions and nutrient conditions of water body, such as metals (Cu, Pb and Zn) metalloids and non-metals (As, Se) and nutrient elements (N, P, C).

4.2.1 Minor solutes (metals/metalloids and non-metals)

Major metal ions are generally most important for the nutrient conditions and salinity of pit lake water while trace metals and metalloids/non-metals are generally most important for toxicity level of pit lakes. These analytes are typically key to pit lake water quality monitoring as their concentrations will fundamentally determine pit lake risk and end use opportunity.

Depending on the mining type, catchment and ore bed geochemistry of a given pit lake, and the closure criteria to be met, a list of metals that should be monitored for can often be generated. For example, gold ore bodies often are associated with arsenic and gold extraction typically involves the use of cyanide. As a result, both these chemicals should feature in an analyte suite for a gold mine pit lake.

Total metals are the concentrations measured in unfiltered samples, with filtering usually at 0.45 μm and dissolved metals are the concentrations measured in filtered samples. Regulatory reporting standards are typically based on filterable i.e. dissolved concentrations which are more biologically available as either nutrient or toxicant. Dissolved concentrations values are also more useful in enabling water chemistry modelling. The comparison of total versus dissolved concentrations can provide the information of metal partitioning between the aqueous and solid phases, which is important to show the fate and transport of metals.

Metal measurements can often be carried out from a routine Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES) laboratory analysis. If the detection limit of ICP-AES is not low enough, graphite furnace atomic absorption Spectrometry (GF-AAS) or inductively coupled plasma mass spectrometry (ICP-MS) may provide a more sensitive method. Many heavy metals and metalloids in Collie pit lakes are below detection by ICP-AES methods (Hinwood *et al.*, 2010; McCullough *et al.*, 2010), yet may be above environment and health background levels. Monitoring of heavy metals and metalloids should be made by ICP-MS to achieve detection limits below pit lake closure criteria concentrations such as (ANZECC/ARMCANZ, 2000a) Guidelines for Protection of Aquatic Ecosystems.

It is important to use analytical grade nitric acid to lower the pH of samples <2 during storage to preserve the sample until analysis. This prevents precipitation and adsorption of metals to the acid-cleaned sample bottles. Once acidified these solutes may be generally stored at room temperatures indefinitely although it is typically easier to transport and store chilled with their adjunct nutrient samples.

4.2.2 Major anions and nutrients

Monitoring the level and distribution of nutrients over time is important in order to be able to understand the biology of pit lakes and of particular importance to understanding algal and bacterial communities. Both unfiltered (biologically unavailable) and filtered samples (biologically available) are typically measured for the major ions of nitrogen and phosphorus as total nitrogen (TN) and total phosphorus (TP).

Nitrogen may be further fractionated into dissolved and therefore biologically available forms reduced ammonia (NH_3) and oxidised nitrate (NO_3), nitrite (NO_2) or a combined nitrate/nitrite parameter (NO_3). The difference between these dissolved forms and the total nitrogen measured is usually due to insoluble nitrogen as organic matter.

Phosphorus may be further fractionated into dissolved form as soluble reactive phosphorus (SRP), more correctly known as filterable reactive phosphorus (FRP) as colloidal material such as clay of 0.45–0.2 µm particle size may strongly bind phosphorus rendering it biologically unavailable. The difference between these dissolved forms and the total phosphorus measured is usually due to insoluble phosphorus as organic matter.

Ion chromatography (IC) can quantify bromide, chloride, nitrate, nitrite, phosphate and sulphate at concentrations often down to tens of ppb level-of-detection. Importantly, IC can also qualify the elements into species of different toxicity e.g., As^{3+} or As^{5+}. Lower levels of detection to ppb can be achieved through colorimetric or gravimetric analyses for example by an auto-analyser or a flow-injection analyser (FIA). A portable spectrophotometer may also be used in field conditions for nutrient analysis. Bicarbonate and carbonate can usually be quantified indirectly from alkalinity and pH.

Nutrient samples should be collected in phosphorus-free cleaned bottles and should be stored frozen until analysis to prevent changes due to bacterial degradation and fractionation and degassing.

4.2.3 Alkalinity and acidity

Carbonate/bicarbonate may buffer lakes at pH of 6 to 8.5 whilst pit lakes of lower pH are often buffered by aluminium complexes (pH 4.5–5.5) or iron complexes (pH 2.5–4). Alkalinity and acidity values indicate the sum of titratable bases and acids in lake water and are needed along with pH. Titrations must be carried out with unfiltered samples and completed soon after sample collection. There should be no air space in the sample bottle and samples should be stored at 4°C until analysis. Due to the complication of performing and method-sensitive, acidity titrations are rarely measured directly; therefore, a calculation from known parameters of pH and acidity-contributing metal concentrations and their speciation is often preferred.

4.2.4 Dissolved inorganic and organic carbon

Dissolved organic carbon can take many forms, the most common of which are tannins in water present as long chain organic acid groups of humic and fulvic acids. Elevated concentrations of dissolved organic carbon (DOC) can decrease mobility of metals consequently decreasing toxicity of heavy metals (Hogan *et al.*, 2005). High DOC concentrations may also strongly attenuate light and may also play an important role in water column photochemical reactions. DOC also sustains microbial foodwebs as an energy substrate in water column ecology (Tittel & Kamjunke, 2004).

Dissolved inorganic carbon (DIC) is the sum concentration of the inorganic carbon forms of hydrogen carbonate (H_2CO_3), bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}). It is important for geochemical changes of pit lakes as the concentration and speciation of DIC affect the solubilities of carbonate minerals, such as calcite, dolomite and siderite, which are strongly dependent on the partial pressure of CO_2.

DIC values can be obtained directly by a carbon analyser (colorimetric titration). Wet perchloric acid or the furnace method with infrared detection is an alternative option. DOC is typically measured by this method on a TOC analyser with a typical detection limit of around 0.1 mg/L as carbon. It is also possible to calculate the concentration of individual inorganic C species based on pit lake pH, alkalinity and temperature using geochemical models, such as PhreeQC (Parkhurst & Appelo, 1999) or ECOSAT (Kinniburgh *et al.*, 1996). For acidic waters with pH <4.5, a carbon analyser must be used to approximate DIC since most of DIC is present as H_2CO_3.

DOC samples are stored as for nutrient samples.

4.2.5 Radionuclides and rare earth elements

If the original mining pit's pit ore body was known to be enriched in long-lived radioactive isotopes (such as ^{234}U and ^{238}U) or shorter half-live but more dangerous isotopes (^{226}Ra and ^{222}Rn), it is important to quantify their concentration as a priority since it may pose a radioactive risk to the surrounding environment. Stable isotopes (such as S, O, Cu, Fe, Zn) and rare earth elements (such as members of the Lanthanides series) can also be analysed for an understanding of dominant biogeochemical reactions in pit lake waters, such as weathering processes, water-rock interactions, mineral precipitation/adsorption and fractionation during abiotic or microbial catalysed reactions.

4.3 Biological analysis

Biological methods of assessing pollution in aquatic environments have the capacity to integrate effects through continuous exposure and because they measure directly the level of change at which a particular stressor becomes toxic. This approach supplants earlier efforts at indirectly estimating toxicity, using chemical and physical surrogate measurements alone (Auer *et al.*, 1990; Karr & Chu, 1997, 1999). Comprehensive and effective assessment and management of water quality relies on integrating biological approaches with the more traditional chemical and physical-based approaches, where chemical data provide explanatory variables for trends observed for biota ("cause for consequence") (Chapman, 1990).

Although chemical analyses can advise us whether water quality is likely to be of environmental detriment, actual biological assessment is needed for the determination of the 'healthy' ecosystem. Assessment of a pit lake's biota is also necessary for the detection of an unacceptable level of environmental risks, the monitoring of short- or long-term changes in pit lake ecology, or the judgement of whether pit lake remediation efforts have been successful. The assemblage (population structure) of different taxonomic (species-type) and trophic (foodweb group) classes of aquatic biological organisms, such as macroinvertebrates, periphytic algae, crayfish, finfish and aquatic macrophyte plants are all appropriate biological indicators for examining pit lake ecological health. However, it must be remembered that many of these biotic groups, especially the more complex orders such as crayfish and finfish, will be responding to habitat quality parameters in pit lakes in addition to any water quality issues of the aquatic ecosystem. Direct measures of diversity by using generic or species-level identification for quantitative studies can be quite expensive and time-consuming. However, some populations of aquatic organisms can serve as biodiversity surrogates if this organism type is found to be reliably responsive to the primary environmental issues of the pit lake. For example, the abundance, diversity and health of pit lake molluscs such as water snails will provide a very good indicator of AMD impact.

It may not be sufficient to simply detect a change in a sensitive or "early detection" indicator, because such a change cannot easily be linked to prediction of a change at the population, community or ecosystem scale in the field. Instead, responses must be sought in the field from suitable surrogates for these higher scales of organisation and complexity (Humphrey *et al.*, 1995) using, for example:

a) species richness, community composition or structure (Baskin, 1994),

b) patterns of abundance and distribution of species of high conservation value or ecological significance (ANZECC/ARMCANZ, 2000b),

c) physical, chemical or biological processes e.g., production: respiration ratios, primary production, energy flow pathways (Bunn, 1995; Davies, 1997; Bunn & Davies, 2000; Boulton, 2003; Kremen, 2005).

4.3.1 Macroinvertebrates

Aquatic macroinvertebrates assist in the breakdown of organic matter from algal and plant growth within and contributed e.g., by lake bank vegetation outside the pit lake. This important community assists in cycling of lake nutrients, and in turn, are food for higher food chain organisms, such as fish. Reflecting their popularity and ease and reliability of identification for biological monitoring of water quality, macroinvertebrates assemblage and composition have been selected as the key indicator group being developed for bio-assessment of the health of Australia's streams and rivers under the National River Health Program (ANZECC/ARMCANZ, 2000a). The Macroinvertebrate Community Index (MCI) (Stark *et al.*, 1999) was developed in New Zealand and is now widely used by Regional Councils to detect and monitor water quality degradation. Similarly Chessman (1995) developed the SIGNAL index (Stream Invertebrate Grade Number - Average Level) for invertebrates identified only to family level in south-eastern Australia. Such biotic indices are based on the rather broad assumption that pollution tolerance varies between species or higher taxa in a manner consistent across all pollution types. Furthermore, such indices are typically developed to be sensitive to urban or rural waterway issues e.g., elevated nutrient concentrations which often differ from those of mining waters e.g., elevated heavy metal concentrations. Apart from analysis of the composition and assemblage of macroinvertebrate communities, functional feeding group measures are other community measures sometimes used for summarising macroinvertebrate community response to water and habitat quality. Functional groups reflect the different trophic levels that macroinvertebrate species feed at (e.g., herbivores, detritivores and carnivores) and hence available food resources.

Pit lake aquatic macroinvertebrate samples should have three or more replicates per lake with a long handled sweep net across either quadrats or linear transects around the littoral fringe (lake margin). A small mesh such as 250 µm mesh is recommended to catch smaller species as community diversity is likely to be poor. The sweep-net is thoroughly reverse-rinsed between each pit lake transect to prevent sample carry-over. Any by-catch of tadpoles and fish can be removed by hand and released back into the pool. Samples are best stored in tight-fitting wide-mouthed plastic jars in cool conditions to prevent loss of preservative. Storage preservative requires at least 70% ethanol and other preservatives with known carcinogenic effects such as formalin should be avoided.

Macroinvertebrate samples are then sorted from underlying sand and organic debris, identified to lowest practicable level (family or below) and then counted. Particularly sandy or gravelly samples, typical of mine lakes, can be elutriated with the lower-density invertebrates washed off from the denser sand and gravel in a manner similar to gold panning. Sample filtrates are then best placed into a four-channel Bogarov tray and sorted by two passes with a stereo microscope. Taxonomic resolution required depends on the monitoring purpose and the resources available to carry out the monitoring.

Due to lack of expertise with database software, macroinvertebrate data is usually entered into spreadsheets. Spreadsheet entry also facilitates data exploration and is an accepted form of data entry into many software packages. Benthic macroinvertebrates can also be sorted into Functional Feeding Group (FFG) categories at this stage (Barbour *et al.*, 1999). The abundance within each group represented the total number of individual animals of that FFG.

Like all biotic community data, the resulting data can be analysed by simple index measures of diversity (number of species or a diversity index such as the Shannon-Weiner for example) or for abundance. However, multivariate statistics are most likely to show more subtle trends in assemblage or community function change than these simpler metrics. Multivariate analyses will best follow a procedure of data transformation, graphical exploration and then final statistical analysis. As an intermediate analysis, the Rapid Biological Assessment (RBA) is developed for stream macroinvertebrate assessment in Australia, as part of the Australian River Assessment Scheme (AUSRIVAS), which is a multivariate system for analysis and assessment of data with broad spatial coverage rather than a single metric or multi-metric approach (Smith *et al.*, 1999). A detailed description can be found in the ANZECC/ARMCANZ guidelines (2000a).

Plate 5. Macroinvertebrate surveys can inform development of site-specific pit lake rehabilitation techniques.

4.3.2 Zooplankton

Another group of biota suitable for water quality assessment is the aquatic zooplankton microinvertebrates. Conventionally, microinvertebrates are invertebrates less than 250 μm in body length that share many of the desired characteristics of macroinvertebrates, but with shorter life cycles and thus faster community responsiveness to environmental change (Van den Brink *et al.*, 2000). Commonly encountered microinvertebrates are zooplankters, either littoral or pelagic. Microinvertebrates are important components of aquatic ecosystems, grazing on detritus, bacteria and phytoplankton and often forming an important link between lower organisational levels of energy (primary producers) and those of higher trophic scales such as the numerous fish species (Fernando, 1994). A significant disadvantage of this group for water quality assessment is their smaller size which may make their enumeration and taxonomic identification difficult and consequently limit their use to more specialised applications.

Due to zooplankton making regular vertical migrations across a pit lake over a daily cycle, zooplankton are generally collected by a vertical plankton net tow from the greatest lake depth by a fine mesh (50 µm or finer) plankton net and then preserved with ethanol and a few drops of glycerol. The plankton net is thoroughly reverse-rinsed between each sample to prevent sample carry-over. Sample vials are also topped up with 100% ethyl alcohol for a final sample alcohol strength of around 80% (Black & Dodson, 2003). An addition of 2% glycerine is recommended to ensure flexibility when identifying later in the laboratory (Woelfl, 2000).

Laboratory analysis involves concentrating the zooplankton sample to 100 mL by gently withdrawing the supernatant from the settled volume using a bulged 10 mL pipette. One mL is then sub-sampled from the well-mixed volume and drained into a 1 mL Sedgewick-Rafter counting cell so that the entire 1 mL contents are identified and enumerated where possible by grid rows. A stereo microscope with 20 times magnification with Nomarski interference contrast optics achieves this well. If taxon identification is not possible within the counting cell and at this magnification, counting cell contents can be decanted into a glass well-block at the end of the count with the suspect organisms extracted for high-powered microscopy (up to 1,000 times magnification) by a compound microscope under oil immersion. Most pit lake microinvertebrates are very small cosmopolitan crustacea e.g., rotifers, but can be identified to genus or species level with keys from Shiel (1995) and more recent keys such as Nogrady & Segers (2002).

Plate 6. Where boat access is not available, a zooplankton net can be thrown and retrieved from shore as a horizontal tow instead.

4.3.3 Phytoplankton

Concentration of chlorophyll-a is a basic indicator of pit lake a phytoplankton algal biomass. Chlorophyll-a can be estimated using a portable fluorometer or spectrophotometer connected to a peristaltic pump. A quick measurement with depth in field can be carried out by using a fluorometer sensor combined with a multi-parameter meter. Due to the presence of “deep chlorophyll maxima” chlorophyll-a is best measured through a depth profile at the lake’s deepest point. A laboratory method is to filter a known volume of water (e.g., 1–2 L) on 0.45 μm glass fibre (GFC) filter paper, digest the algae collected on the filter paper with a solvent such as acetone and then measure the resulting digest chlorophyll-a concentration and relate this to lake chlorophyll-a concentration by spectrophotometry, or more accurately by fluorometry.

Phytoplankton assemblage should also be collected for maximum information on in-lake foodweb development and resilience by collecting surface water samples by hand, or column via a discrete sampling device, and then fixing with excess Lugol's iodine.

Water body chlorophyll *a*, *b* and *c* concentrations can be used as proxies for phytoplankton biomass and general composition. The concentrations of these different photosynthetic pigments may, therefore, be expected to act as proxies for phytoplankton assemblages (Jeffrey *et al.*, 1999).

4.3.4 Periphytic algae

Another important source of primary production for communities of littoral habitats is periphyton assemblages which are also widely regarded as good bioindicators of ecological change (Dixit *et al.*, 1992). Due to the presence of good taxonomic information and easy preservation, diatoms are generally the most common periphytic algae monitored for. Diatoms are also generally relatively sensitive to changes in water chemistry (e.g., nutrients and salinity), are easily collected (by meshes), analysed and preserved, and can be readily identified to species scale (Patrick *et al.*, 1968; Reid *et al.*, 1995). pH has often been found to have the greatest influence on diatom assemblage, with most species showing a preference for a narrow pH range (Denichola, 2000). Nevertheless, the application of diatoms as bio-indicator for water quality may be limited because of their small size and requirements for preparation prior to sorting and expert identification (Reid *et al.*, 1995).

Artificial substrates for periphyton sampling ("periphytometers") can used to quantify diatom community structure in ongoing monitoring programs to control for substrate differences between different water bodies such as when comparing assemblages from pit lake and natural water bodies. Unlike many of the other taxonomic groups studied, there are no established standard methods for assaying diatom communities (Aloi, 1990). Given the lack of standardisation in the use of artificial substrates in periphyton studies (Reid *et al.*, 1995), there should also be an emphasis on thorough documentation of any methodology used to facilitate data and study result interpretation and to assist in monitoring consistency.

Periphytometers used to sample benthic diatom communities can consist of an acrylic plastic frame with 10 glass microscope slides (25 mm x 75 mm x 1 mm = 18.75 cm^2 surface area on each slide side) inserted vertically (John, 2000a, b) so as to reduce the extent of siltation through settling of suspended solids (Biggs, 1988; APHA, 1998). This periphytometer design and slide orientation is one of the most common forms of artificial substrate recommended for experimental studies (Aloi, 1990; APHA, 1998).

Plate 7. Artificial substrates, such as this glass slide-based 'periphytometer' allow easy quantification of periphyton abundances.

Prior to use, new glass slides are first rinsed in phosphorus-free laboratory detergent and then soaked in 5% HCl for 48 h to remove production residues. Due to variation in light climate and risk of vandalism or loss, multiple replicates should be deployed, with each periphytometer placed on the sandy benthos in wadeable water around the edge of the pit lake. Periphytometers are typically deployed for at least two weeks of exposure before being retrieved. The periphytometers are then wrapped in wetted cloth and placed in the dark in an insulated container containing ice-cold water for return to the laboratory where they were fixed. Upon return to the laboratory, each of the 10 slides from each periphytometer can be carefully scraped clean with a razor blade into 30 mL of demineralised water, and a few drops of alcohol and 3–4 drops of Lugol's solution added.

Alternatively, diatom and other periphyton scrapings can also be made by scraping the surface of rocks, woody debris and sediment and algae into a small vial with a finger. Diatom scrapings are then made up to *ca.*50 mL with water and preserved with a few drops of ethanol. Although diatom assemblages sampled may not have developed from a community identical to that on the nearby sand substrates, they still represent valuable bioassay data from a high scale of ecological complexity and relevance (McCullough, 2009).

Diatom sorting methods may follow Battarbee (1986), with the exception that samples from acidic pit lakes will not require the first treatment of HCL as it was not necessary to remove carbonates from samples.

Aliquots of around 1 mL of well-mixed periphyton sample are identified and counted under a compound microscope until 300 valves are reached. Percentage cover slip area covered to reach 300 valves is also recorded so that samples can be standardised to total cells/cm^2. Valves can be identified using the keys of Gell *et al.* (1999).

4.3.5 Freshwater crayfish

Freshwater crayfish can be a good indicator to monitor the toxicity of polluted water. It has been used as direct toxicity assessment of waste water in Australia, and there is available for cadmium and zinc chronic data in freshwater guidelines and for aquatic toxicology data of some non-metallic inorganic chemicals. A crayfish fishery can contribute to sustainable economic opportunities for pit lakes in a post-mining landscape. For example, the large endemic freshwater crayfish marron (*Cherax cainii*) provides a prized recreational fishery in many regional parts of south-Western Australia, including Collie (Whiting *et al.*, 2000). Marron has been introduced to Collie pit lakes along with other non-fishery species of crayfish. However, bioaccumulation of metals in crayfish can also be a concern as high metal concentrations may be high in some pit lakes (McCullough & Lund, 2006).

Crayfish can be captured with baited 'Opera House' or box traps set overnight around the littoral margin of a pit lake (Campbell & Whisson, 2000) (Plate 8). Crayfish can also be captured by sweep nets and 10 m Japanese Seine transects along the pit lake littoral fringe during the day.

Plate 8. A successful catch of crayfish in a pit lake by a box trap baited with cat biscuits.

4.3.6 Finfish

Finfish populations and/or communities are good biological indicators for environmental stress encountered in pit lakes at a variety of levels from water quality, through to food and habitat availability. As finfish represents around one-third of total aquatic food production in value and quantity in Australia (ABARE, 2009), aquaculture of finfish can also add the economic value of pit lakes. Finfish can be captured with a 10 m Japanese seine (Plate 9) or by sweep nets along the littoral fringe. Due to habitat variability around the edge influencing fish distribution, ideally at least three beach transects should be taken at each pit lake. However health and safety issues can be problem due to steep banks which may reduce the chance of effectively sampling. Fish recovered to the beach should be immediately placed into a bucket of clean water and be anaesthetised with a registered fish anaesthetic such as

Benzocaine, Phenoxy-ethanol or Aqui-S. After species identification and length and or weight data collection, they should be then allowed to recover in a bucket of clean water and then returned live back to the lake.

Sometimes monitoring management can not focus on finfish due to the numbers of individuals being too low to monitor the population reliably. The monitoring program should therefore also include some other finfish fishery biomass and diversity indicators such as littoral habitat structure and aquatic vegetation structure and proportion cover that provides crucial habitat for finfish.

Plate 9. Seine sampling in deep water can be made with boat assistance operators on the adjacent bank.

4.3.7 Aquatic plants

The growth rates of aquatic plants (or macrophytes) in pit lakes are related to the concentration of key nutrients in the water column and the biomass is mostly controlled by the total mass of these nutrients available. Low concentrations of nutrients are often the limiting factor for aquatic plants in pit lakes. However, in many cases, the water column nutrient concentration is not a good indicator of macrophyte biomass. For example, the net water column nutrient concentration could be quite small in an ecosystem with a high algal biomass but with rapid nutrient cycling.

Limiting factors for species composition and diversity in pit lakes typically include low pH (Fyson, 2000) high concentrations of metals (Yan *et al.*, 1985) and low nutrient concentrations. Under high sediment nutrient loading, this resistance to nutrient limitation may not be encountered as P in sediments may be more bioavailable under reduced redox conditions caused by decaying organic matter (Aldridge & Ganf, 2003).

Nonetheless, steepness and resulting littoral bank stability may limit aquatic macrophyte establishment even where pit lakes water quality is good. Consequently, an assessment of bank topography around a pit lake and including steep highwalls and shallow bay representation and any resulting seral succession across the varying topography of these sites may provide useful insight into whether or not pit lake macrophytes are actually water quality limited or are habitat quality limited.

5 Additional water quality indicators

To complete the chemical, mineralogical and microbial analysis for the whole system of pit lakes, some other less critical samples are recommended. This type of information may not be critical for regulatory monitoring programs for pit lake water quality; however, it is a very useful for the background analysis and long-term monitoring and it is also needed to be considered as a part of assessment when the decision is made for different remediation approaches. It includes ground water and surface water, sediment and pore water, and soil, rock and vegetation in catchment area.

5.1 Groundwater and surface water

Groundwater and surface water are the important source of pit lakes in term of water volume and chemical inputs, which determines largely the characteristics of a given pit lakes. Hydro-geological information on flow and quality of groundwater and surface water is necessary for the calculation of a sites' water balance input; the characterization of in-situ conditions (baseline); the evaluation of the fate and transport of interested chemicals; and the assessment of acid or metals source and process.

A temporal and spatial component should be included in the groundwater monitoring design. Information on the site geology, topography and hydrology should be reviewed to develop a conceptual model of groundwater flow directions before siting monitoring wells. A minimum of three groundwater level measurements from the same aquifer are required to determine groundwater flow direction. Well sites should consider groundwater flow directions and velocity. Sampling program should be in fixed frequency in part determined by the dynamics of the system being monitored e.g., existing regional scale datasets can inform groundwater monitoring sites and frequencies. For example, monthly groundwater level measurements and quarterly groundwater quality sampling. The well should use acid or sulphate resistant materials, such as PVC or stainless steel. Detailed information can be found in AS/NZS-Water Quality sampling, Part 11: Guidance on Sampling of Groundwaters

(AS/NZS, 1998) and NEPC – Schedule B (2) Guideline on Data Collection, Sample Design and Reporting (NEPC, 1999).

Surface water adjacent to pit lakes may include rivers, springs, streams and wetlands, including damplands. Depending on the climate, some of them may only occur seasonally by wet season or temporally by sudden rainfall. They can be both water source and acceptor of pit lakes. The important parameters include gradient, width and depth, substrate composition, flow characteristics, pool frequency, temperature and dissolved oxygen. The erosion of waterside bank can also be relevant for pit lakes. Detailed information can be found in ANZECC/ARMCANZ, (2000b) – Australian and New Zealand Guidelines for Fresh and Marine Water Quality.

5.2 Lake sediment and pore water

Lake sediment and pore water chemistry can give important information about mineral precipitation rates from lake water and their likely effects on water chemistry and microbial activity and nutrient cycling in lakes sediments. These data add considerable value to more accurate geochemical modelling of pit lake water quality over time. An intact core sample can be obtained by dropping a weighted sampler by gravity down to the bottom of the lake (Plate 10). Alternatively in deeper water bodies or with softer sediments that are not as well contained in the core, a diver may retrieve a sediment core using an acrylic tube and rubber bungs (Plate 11). The sample column can then be removed back to the surface and sectioned for analysis of pore water chemistry (pH, Eh, DOC and dissolved metals), sediment mineralogy (e.g., X-ray diffraction, scanning electron microscopy) and solid-phase chemistry (e.g., isotope dating and total metals). A special care of sediment samples is, however, needed if changes to redox status are likely to occur, for example, Fe(II) / Fe(III) measurement. This can be avoided by the direct sealing caps *in situ*. Pore waters in sediment can also be extracted by filtration or centrifugation in laboratory. Diffusion samplers (such as DGT) can be used to collect *in situ* samples which need long time for diffusion processes (Plate 12). This method is not only suitable for shallow sediment as divers can be utilised in their deployment and lines attached to floats used for their recovery.

Plate 10. A “bomb” benthic sediment piston sampler being deployed into a pit lake from a small boat. Note winch to retrieve in left foreground.

Plate 11. Divers can collect sediments from pit lakes using simple acrylic cores.

Plate 12. A diffusion sampler showing cells offset at 10 mm intervals along its length.

5.3 Soil and rock in catchment

Soil and rock samples are important as the runoff from the catchment area may affect the geochemical conditions of lake water and may continuously bring nutrients and toxic metals to water body which in turn influence microbial activity and nutrient cycling. The background information of soils and rocks in the catchment may be easily obtained from the mining operation. However, a long-term monitoring is still needed since the soils may develop through the new vegetation establishment. The sample locations must be planned according to the size of the catchment and access possibility. Topsoils (often around 0–15 cm) and subsoils (often around 15–50 cm) are needed for physical analysis (particle size fraction) and chemical analysis (pH, Eh, DOC, total concentrations and speciation of metals and mineral compositions). Diffusion samplers (such as DGT) can be used to collect in situ soil solution samples which need long time for diffusion process.

5.4 Riparian and catchment vegetation

Monitoring water quality of pit lakes is not only to maintain the environmental values of water body, but also to assess integrally the surrounding environment connected with pit lakes e.g., for visual aesthetics and sustainable development ecosystems. The development of riparian vegetation plays an important role on nutrient input of pit lakes, enhancement of water quality, as a habitat of aquatic organisms and animals and preventing polluted drainage inputs from catchment soils. Riparian vegetation composition and structure responds to water flow, temperature, salinity, etc. and is a good bio-indicator for overall pit lake ecological health. Some parameters of riparian zone are also useful for pit lakes monitoring, and include width, percent cover and composition of vegetation and estimated shaded area by season.

It takes a long time to develop riparian vegetation around pit lakes since mine walls are typically steep, unstable and lack of nutrients for growing plants. Nevertheless, by planning in advance, the mine walls of pit lakes can be well structured into more gentle slopes suitable for vegetation. Monitoring can then advise this process on whether the slopes and soils are sufficiently to allow a regionally representative riparian community to develop. Some topsoil coverage and fertilizers may also solve the nutrient deficiency. One generic biodiversity-type protocol has been developed for wetlands using remote sensing to map and monitor vegetation distribution, vigour and structure (details in Appendix 3, Method 5, the ANZECC/ARMCANZ guidelines (2000b)). It is also possible to detect the changes of vegetation structure in a large area of catchment.

Plate 13. Surveying pit lake riparian and catchment vegetation is often best made along transect lines running perpendicular to the lake.

6 Health and safety

Field health and safety is an important part of the monitoring project plan. Effective sampling of pit lakes often requires a boat and therefore it should follow the usual safety hazards associated with open water and operation of a vessel are required. Federal, state and institutional boating and working around deep water protocols should be followed in this regard.

There are also further special attentions needed in sampling of pit lakes. Unstable pit lake walls may result in landslides leading to surge waves which can easily capsize a small boat on the water. Dangerous gases, such as carbon dioxide and hydrogen sulphide, may be released in the event of a partial or complete lake turnover which are heavier than ambient air and form a lethal layer of CO_2-rich or H_2S-rich and O_2-poor air just above the lake surface. Sampling activities often happen in a telecommunication-free zone, therefore cell phone or radio phone may be needed double-check and a “buddy system” is essential where a clear line of communication between personnel on the boat with personnel on land in case of engine failure or other emergency situation.

6.1.1 Personnel

Permission required for a fieldtrip to access any private or government site should be obtained well in advance to entering the site. An induction may be required by the owned company before work on site. To ensure that appropriate site personnel are aware your entrance and safely exit of the site, you should sign in and out of a visitor’s book each day.

Whilst working in a remote area or around water an individual must always be accompanied by another competent person. Each team member should complete a risk assessment form prior to field sampling. At least one member of the team should carry a proficient accredited Senior First-Aid certificate. Where field work is occurring in a remote area (defined as time to assistance and not be simple distance alone) a Remote Area First Aid certificate should be carried by at least one team member. The fieldtrip leader needs to be aware of all personnel health issues prior to the fieldtrip and first aid qualifications. In addition, at least one of the sampling organisation's staff not going on site must be given the team's itinerary, risk assessment forms and contacted at the end of each day.

For operational areas, each individual needs to be wearing basic industrial PPE steel capped boots, long trousers, long sleeved shirt (with reflective strips), safety sunglasses and hard hat. For non-operational areas, standard field dress such as broad brimmed hat, sunglasses and light cool fabric clothing and use of sun screen are required for hot weather. Cool weather areas will similarly dictate appropriate field work clothing such as wet weather gear. Note that these clothing requirements are likely to be a minimum for most mining company operational requirements and that other PPE such as wearing gloves may also be required. The fieldtrip leader needs to ensure that individuals meet clothing requirements and carry spare sun-cream, a field first aid kit (including snake-bite dressings), blanket and more than adequate water for all team members (at least 2 L of water per person per day in cool weather and at least 4 L of clean drinking water per person per day in hot weather).

The fieldtrip leader should ensure one reliable personal communication device is present at all times while on site. In operational areas with good mobile coverage a weather protected mobile phone (e.g., snaplock bag) will suffice. Also a handheld UHF radio will often be available from the administration office for direct contact with vehicles and an emergency number will suffice over short distances and direct line of sight. In out of reception areas an EPIRB (Emergency Position Indicating Radio Beacon) satellite phone (preferred) will be required.

6.1.2 Driving and 4x4 access

A vehicle will typically be required to access the study site. Given rehabilitation efforts and road decommissioning around the pit lake, a 4x4 will often be the vehicle of choice. As required by law in Australia, only team members with the appropriate licenses should drive vehicles and no 4x4 vehicle should be driven off-road without 4x4 driving experience and knowledge of vehicle recovery equipment and procedures. If a vehicle is fitted with a UHF radio ensure that all relevant safety and operational radio channels used on site are known by the field team before entering the site.

Mining company-required vehicle signage, flags and lights should also be displayed on the vehicle whilst on site.

To minimise damage to vegetation and the vehicle becoming bogged, stay on designated tracks or roads whilst driving. If, however, required to venture off-road at any point in the journey, the 4x4 vehicle must have a recovery kit on board. The kit should contain minimum: snatch strap, shackles, hand/electric winch, tree protectors, deflators, compressor, jack, basic tool kit, high lift jack and at least one spare wheel. In particularly remote or rocky areas a high lift jack and at least two spare wheels should be carried.

6.1.3 Working around water

The fieldtrip leader needs to ensure individuals are aware of any particular dangers at the site, such as unstable pit banks or water quality which may be harmful to contact skin. All personnel working around water must wear a life vest or life jacket. Rescue equipment such as a thick rope (10 m or more) should be carried to assist personnel in the water, or entrapped in soft sediments, to safe ground. When working in a cold weather environment, then personnel working in or around water should carry a set of dry clothes to minimise the risk of hypothermia.

Launching boats and carrying any equipment more the 15 kg must be done in a safe manner i.e., the load should be shared by more than one person with proper lifting techniques.

6.1.4 Boating on pit lakes

Use of a wide bottomed ‘punt’ type boat will afford greater stability when collecting samples from the sides of the boat. The size of the boat must be practical for the number of individuals and equipment required. To ensure, check boat capacity through the boat manufacturer’s guidelines and avoid overload.

The boat operator must be experienced in small boat control, launch and recovery. Additionally, State boating regulations must also be adhered to, for example, in Western Australia, if the power of the boat’s motor is greater than 6 hp, the boat operator must have a Restricted Coxswain when the vessel is being used for commercial activities by research or industry organisations.

Safety equipment should be carried on board at all times, including extra fuel, bailer bucket and a basic tool kit (including spare spark plug for motor of boat, sparkplug socket, spanners and screwdrivers). A set of oars or paddles as back up if motor fails and is irreparable, spare bungs for the boat in case of loss or damage to existing ones and an anchor to stop the boat from drifting are also essential boating equipment. A water tight container with flares and torch may also constitute essential equipment on large and/or particularly remote lakes.

There should also be at least 5 m of thick rope for use as a bow line to shore anchor, retrieve and handle the boat in windy conditions. The boat's bow line may be used as a rescue line to assist personnel in the water back to boat.

Prior to leaving shore the boat operator will conduct pre-checks, including ensuring motor is in good working order, all safety equipment (detailed above) is stowed on board and boat is in good working order, bung plugs in place, no visible leaks and boat not overloaded, all personnel are wearing a life vest or jacket. It is also a good idea to have the boat engine running well before cast off from shore. To minimise the risk of capsizing individuals must remain seated as much as possible in order to trim and maintain stability of the boat on the water.

6.1.5 Diving considerations

Due to the inherently increased hazard of venturing underwater, diving should be avoided where possible. As part of the field trip risk assessment, scenarios where diving is planned should be examined for alternative options, such as using ropes to remote sampling devices for sediment samples or remotely triggered water samplers, or even by using an underwater viewing device (bathyscope or submergible camera) and lines to lower and then retrieve sampling equipment from an appropriate placing.

When diving must occur, divers must be minimally qualified e.g., PADI (Professional Association of Dive Instructors) Open Water or equivalent and be experienced for the conditions that they may reasonably encounter during the course of their dive e.g., deep diving and low visibility diving.

Prior to the commencement of a diving expedition, a dive plan must be authorised by a dive officer within the organisation. Serviceability of all equipment should be checked prior to the dive including BCDs (Buoyancy Control Device) and regulators (including primary and secondary stages) being maintained within a 12 month service interval. All diving teams must have a dive supervisor with a Stress and Rescue ticket equivalent (PADI) or higher e.g., Master Diver or Dive Master. The dive supervisor is responsible for ensuring the safety of all divers and logging dive details such as maximum depths, bottom times and repetitive factor groupings, when multiple dives are planned. Divers should have a current accredited Senior First Aid certificate and DAN (Divers Alert Network) oxygen provider certificate. Divers may also be required by state regulations to satisfy specific medical requirements when diving in a working capacity. For example in Western Australia the Department of Occupational Health, Safety and Welfare require all occupational divers to have a current AS2299 medical or higher. A surface support person must accompany each dive team either on the boat or on shore to watch for any dangers on surface, location of divers at all times and to aid divers with equipment and samples whenever entering and exiting water. Oxygen resuscitation equipment should be at hand by the surface support person.

All divers should wear a wetsuit for both exposure and abrasion protection and carry a snorkel to reduce air tank reliance when on surface. A BCD should be used to ensure good buoyancy control including neutral buoyancy to minimise fine sediment disturbance. A compass should be carried to improve underwater navigation efficiency therefore reducing immersion times and also in case of unexpected low-visibility events following fine sediment disturbance. All dives must be carried out using a ‘buddy’ system i.e., divers must always dive in a minimum of pairs so as to provide support to an at-risk diver. As an added safety measure each diver should surface with no less than 50 psi in the air tank as a reserve.

All ascents and descents must be controlled and safety stops carried out at 5 m for 5 minutes. Dives of 20 m or more require an additional first safety stop at 8 m for 3 minutes. A dive computer will indicate when any additional safety stops are required and for how long. The DCIEM (Defence and Civil Institute of Environmental Medicine) diving tables should be used as standard practice for all dives to ensure adequate surface intervals and appropriate repetitive groupings are observed for non-decompression dives and should be used in parallel with dive computers. Dive tables also give conservative and reliable safety stop times which need to be understood by the divers before each dive in case a problem with the computer is encountered during the dive. The use of controlled descents and ascents required to reduce the risk of divers surfacing with decompression issues.

When diving in areas where the general public have access a large dive flag must be used on the surface (on boat or shore) to indicate the presence of divers below and the 50 m exclusion zone. However, when working in an area of restricted access one diver per ‘buddy’ pair should carry a small dive flag with float to assist the surface support to identify the location of divers easily.

7 Budget

The costs of a monitoring program include labour, materials, and other related expenses in the project. A prediction of the costs associated with monitoring project, and has to be considered carefully according to the monitoring objectives. Ideally, one should only determine the required budget after the monitoring plan designed has been constructed that will clearly meet monitoring objectives. However, in reality, the budget often comes together with the monitoring project and will always be a limiting factor for what variables the monitoring project is able to investigate and to which spatial and temporal resolution.

Nevertheless, indispensable sampling variables and their spatial-temporal frequency required to achieve monitoring objectives should not be compromised by the budget. Similarly quality assurance processes such as replicates and blanks remain vital to the resulting dataset's value and should only be reduced to minimum practical levels and never omitted altogether. Health and safety requirements may often be fixed by the lease holder of the pit lake e.g., mining operation. However, significant savings may be tempted by reducing staffing levels in the monitoring field team e.g., to a single person collecting the sample. The fundamental safety requirement when working on and around water of a minimum two people is too significant and must, however, never be compromised.

Outside of staffing levels, health and safety considerations are unlikely to provide significant savings to a monitoring programme and should never be a focus of budget tightening. Instead, an iterative approach of culling expenses from least required (least informing) sampling should be followed to identify where budget saving may be made (Figure 10).

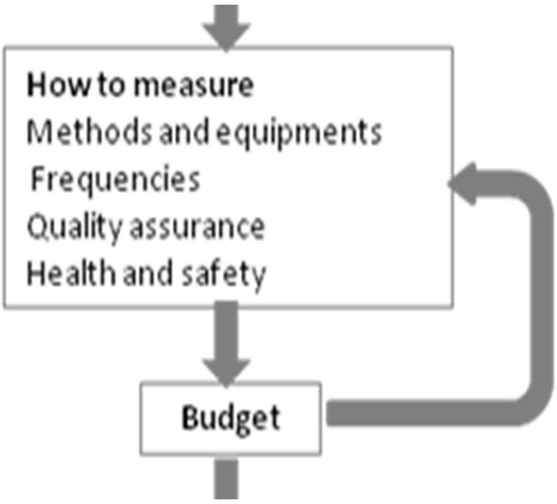

Figure 10. Detail of iterative budget development and refinement recommended for a pit lake monitoring program.

8 Sampling frequency

Monitoring strategies for pit lakes are complicated due to varying climatic, physical, chemical and hydrological characteristics of different pit lakes. Firm guidance on sampling parameter suite and sampling frequency cannot be given without accounting for the end use that a pit lake is being used for. However, based upon how new to the landscape the pit lake is and how well its limnological and ecological characteristics are (or will be) understood, some general sampling guidelines can be recommended for two basic pit lake types; historic pit lakes and new (newly-formed) pit lakes. The title of historic pit lakes carries an assumption of final water depth, and water quality and ecology representative of a longer term. New lakes include those newly filled or filling, or lakes undergoing targeted restoration or remediation, be it active or passive. These lakes will generally have poorly understood water quality and ecology and may continue to evolve at a rapid rate in the future in a poorly-defined trajectory. This general guidance may be over-ridden by specific characteristics and requirements of the pit lake. For example *ad hoc* compliance requirements from regulation agencies, necessities of industry operations using the lake as a resource, and the desired or realised end uses of surrounding communities.

8.1 Once-off monitoring

Lake morphology, geological and ecological background information must be established in some detail. A digital elevation model (DEM) is a digital representation of ground surface topography. As a single data collection, a DEM of the lake catchment should include pit morphology data e.g., from production Vulcan models, as well as rehabilitated catchment morphology data (Table 2). These data will enable modelling of geo-chemical and hydrological processes between pit lakes and groundwater as well as enabling modelling of catchment processes such as surface water contributions to lake water quality. Accurate soil porosity and storability may be required for ground water modelling, however, basic geologic knowledge typically available from active mining regions such as descriptions of major aquifers and aquicludes intercepted by pit workings will often be available and very useful for both modelling and general understanding of current water quality and evolution.

Contribution to the pit lake catchment from backfill should be well understood, both as masses, placements and for their acid/base accounting.

Lake sediment type may also influence water quality; both through storage and release of heavy metals and nutrients (Batley & Maher, 2001; Blodau, 2006). To make numerical water quality models more reliable, sampling sediment from different locations within the Collie pit lakes are strongly recommended. The sampled sediments should be analysed for physical and geochemical properties such as active porosity, composition of pore water and cation exchange capacity. Mineralogy and geochemistry may also be determined by X-Ray Diffraction (XRF) and sequential extraction techniques. If possible, sediment samples should be taken as columns to get information about vertical distribution of these properties. This can provide a basis for estimating the total amount of acidity in the sediments in addition to the rate of its release and composition over time. In the same manner as the subaquatic sediments, bank material should be analysed to identify zones for which erosion rates and their impact on lake water quality can be modelled.

Table 2. Recommended once-off sampling for pit lakes and their catchments.

Parameter	Details
Digital elevation model of catchment	Lake bathymetry and catchment topography
Groundwater stratification	Major aquifers and aquicludes intercepted by pit
Pit backfill	Geochemistry and acid/base accounting
Lake sediment	Geochemistry and mineralogy
Catchment vegetation	Community structure, height, coverage

8.2 Historic pit lakes

Historic pit lakes may have existed for decades, will typically have completed filling and will often have existing water quality datasets and generally well understood annual variation and consequently potential environmental risk. Local communities may have been using the lakes (often even without remediation) as recreation sites in an organic manner for some years. Nevertheless, if the lake is used for bathing or other recreational contact such as water skiing it should be monitored regularly potential human health risks as per any other bathing water body.

Ideally seasonal, or at a minimum yearly, sampling is needed for long-term monitoring datasets to advise comprehensive management of risk and utility (Table 3). Sudden events include onset of remediation treatments, strong storms, sudden water influx or efflux may require either ad how or more frequent monitoring as for new lakes to establish water quality effects and disturbance consequence on the lake ecology. The dataset gathered for long-term monitoring of historic pit lakes will also provide valuable information for research purposes to better understand pit lakes particularly in the region or context of the monitored lakes, such as lake stratification, geochemical process and ecological evolution. A well-established monitoring dataset will also give precautions about salinity increase, which can be further modelling predicted. Moreover, it provides information to protect end users, such as recreational activities or aquaculture, from health risks. Based on the long-term monitoring, some successful remediation may then be instigated for social and economic benefit, for instance, aquaculture and irrigation.

8.3 New pit lakes

New pit lakes are the lakes formed after the recent cease of mining operation which are in the process of filling up slowly or rapidly by surface water or ground water. Short-term monitoring with greater frequency is also suitable for tracing pit lake characteristics which are still becoming established following a change of inflow water such as through groundwater rebound or fast filling strategies. Monthly or at least seasonal sampling is needed and the short-term monitoring program should cover at least 3 years, ideally longer where uncertainties such as due to a variable climates, are greater.

Less frequent seasonal sampling is needed for long-term monitoring of new-formed pit lakes (Table 3). Again, issues and parameters identified by regulatory requirements should be emphasised in the monitoring program. Conversely, potential remediation options may be suggested by judicious sampling for water quality patterns in a well-established monitoring dataset. New lake monitoring includes both normal new unrehabilitated and rehabilitated lakes as well as those undergoing remediation.

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Table 3. Minimum recommended sampling frequency for pit lakes. Major seasons e.g., temperate Summer/Winter or Dry/Wet seasons. *only required if end use required contact values e.g., swimming and water skiing. [π]Only required if end-use requires environmental values e.g., as wildlife habitat.

Parameter	Position	Historic lakes	New lakes
Water			
Depth		Seasonally	Monthly
Temperature	Profile	Seasonally	Monthly
Conductivity	Profile	Seasonally	Monthly
pH	Profile	Seasonally	Monthly
Dissolved oxygen (as % saturation and mg/L)	Profile	Seasonally	Monthly
Turbidity	Profile	Seasonally	Monthly
Light attenuation (KD_{par})	Profile	Seasonally	Monthly
Groundwater inflow/outflows		Seasonally	Seasonally
Surface water inflow/outflows		Seasonally	Seasonally
Chemical			
Dissolved metals/metalloids	Top (bottom waters also if stratified)	Seasonally	Monthly
Major anions	Top (bottom waters also if stratified)	Seasonally	Monthly
Major nutrients (TP, FRP, TN, NOx, NH_4, DOC)	Top (bottom waters also if stratified)	Seasonally	Monthly
Buffering capacities (acidity and alkalinity)	Top (bottom waters also if stratified)	Seasonally	Monthly
Biological			
Faecal indicator bacteria*		Monthly	Monthly
Aquatic macroinvertebrates[π]		Seasonally	Seasonally
Zooplankton[π]		Seasonally	Seasonally
Periphytic algae[π]		Seasonally	Seasonally
Phytoplankton (chlorophyll-a)		Seasonally	Seasonally
Crayfish[π]		Annually	Seasonally
Finfish[π]		Annually	Seasonally
Aquatic macrophytes[π]		Annually	Seasonally
Riparian vegetation[π]		Biannually	Annually

9 Recommendations

A monitoring strategy for pit lakes has been identified as critical to realisation of end use benefits such as water resources for agriculture and aquaculture (McCullough *et al.*, 2009). Although there are significant datasets of historical data for many of the Collie Region lakes, many of these data have been collected in an *ad hoc* manner and there are many inconsistencies between different occasion of collection that render collation and compilation problematic (McCullough *et al.*, 2010). Many large new lakes have had almost no monitoring afforded to them (e.g., WO5B and WO5C) whilst others have been heavily monitored for single parameters, but with an absence of supporting parameters. For example, Lake Kepwari was monitored regularly from 2005–2007 for pH, yet other valuable water quality parameters such as conductivity and Eh were not recorded for most of this time.

The Collie pit lakes have and will continue to interact with their surrounding environment over time. The Collie Lake District also represents a vast volume of potential useful water as a highly significant natural resource for south-western Australia. Risk assessment and management strategies would benefit from a better understanding and better prediction and it is therefore necessary to monitor of pit lake water quality and its aquatic biota. Pit lake water quantity and quality may also change under climate change e.g., under a drying climate, and high quality monitoring datasets are required to provide both modelling input and model validation data to characterise these risks.

- A comprehensive monitoring programme has now been developed (this report) but still needs to be implemented in the pit lakes for a better understanding of whether or not pit lake water quality will meet end use criteria for current activities now (e.g., swimming) or proposed activities (e.g., fishing) into the future.
- Ultimately pit lakes will evolve to become dominated by biological rather than chemical processes; however the consequence of this is unknown. A detailed monitoring program to monitor changes in biological communities is therefore also needed to provide information

on whether the pit lakes will be able to provide ecological valuable environments to the region.

The Collie Region's groundwater is thought to be the main recharge and discharge source of the Collie pit lakes and the water qualities of pit lakes are thought to be predominantly controlled by groundwater. Information on the quality and quantity of groundwater entering and leaving pit lakes is essential to allow proper acidity and water balance budgeting. A study is therefore needed to understand groundwater flow in and out of Collie pit lakes.

- A better knowledge of groundwater near pit lakes; especially with regard to newly forming new pit lakes is essential. This could be achieved through both once-off investigations into catchment backfill characterisation and also from a simple groundwater monitoring program from bores placed close to representative pit lakes.

There are many datasets where sampling has included replicates of surface water quality (understood to be largely homogenous in pit lakes) which have, however, ignored, vertical replication of water sampling as a stratified sampling design. For future monitoring to be able to provide useful analysis of pit lake water quality, a move must be made away from surface water samples only, toward a better understanding of the entire lake water column. An understanding of when and what durations stratification occurs under, and how water quality and aquatic ecology responds to this is also needed.

- Replication of single depth e.g., surface water samples, are likely a waste of sampling effort and could be dispensed with to reduce sampling and analysis budgets without loss to any monitoring data value. Future monitoring attempts must, however, take into account basic limnological monitoring facets such as water column profiling. Specialised equipment will be required for this as lake water column depth is very great, particularly in the new pit lakes.

A number of the pit lakes are already or are predicted to discharge into natural water bodies (e.g., Stockton, WO5F, WO5H, Lake Kepwari, Black Diamond A). However no monitoring datasets were encountered in the Inventory of Collie pit lake water quality and no ecological assessments appear to have been undertaken of the ecological impacts of this discharge on downstream receiving environments. These data are also fundamental to understanding the consequences on downstream water quality and aquatic ecology from such proposal as a permanent diversion of the Collie River through pit lakes such as Lake Kepwari.

- The quality and quantity of surface discharge from pit lakes needs to be understood through monitoring and the ecological impacts of surface discharges needs to be fully investigated.

Some lakes have undergone rehabilitation in their catchments (e.g., many new Premier pit lakes) whilst other pit lakes have undergone deliberate remediation strategies (e.g., Lake Kepwari) or are undergoing incidental remediation e.g., Lake WO3 through the adjacent Aquafarm. Nonetheless, none of thee lakes are currently being monitored in any coordinated strategy. Hence, any information on which remediation strategies may work, and to what varying extend with what limitations; is being lost.

- Little is known about remediation approaches that might be successfully employed to treat water quality issues in Collie pit lakes. Monitoring of pit lakes representative of different rehabilitation and remediation attempts should be made in order to advise which of these approaches may be of use with the predicted, much larger, new pit lakes.

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